

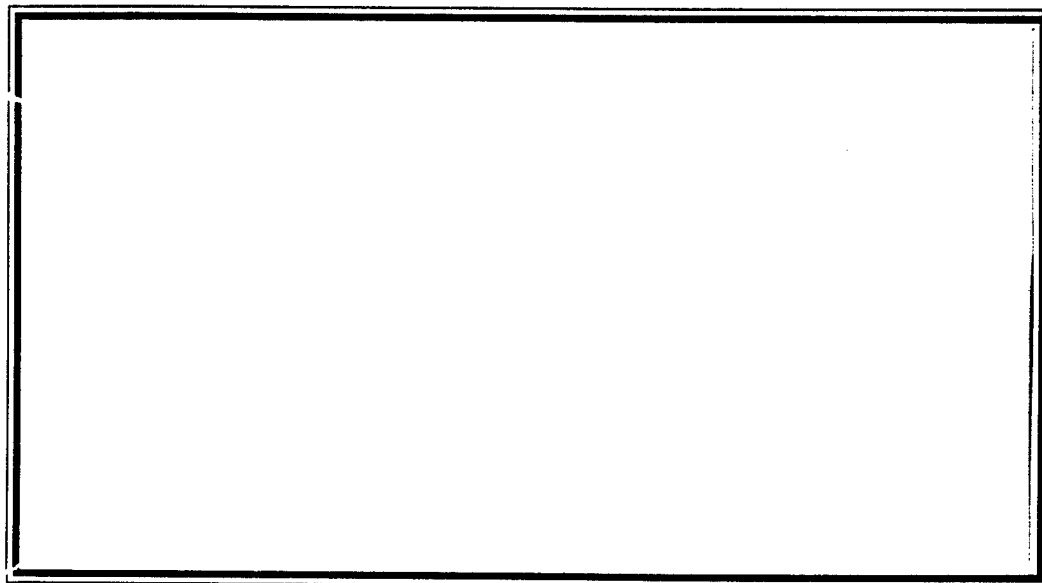


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**MODEL-BASED MEASURES FOR THE  
ASSESSMENT OF ENGAGEMENT OPPORTUNITIES:  
IMPLEMENTATION AND TEST RESULTS**

by

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November / novembre 1998

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## ABSTRACT

Analysis results are presented from the application of new DREV-developed methods for studying, analyzing and assessing the value, usefulness or goodness of the tactical information used by maritime commanders in decision making, in particular for over-the-horizon targeting. These methods relate information quality and system measures of performance (MOPs) to decision and mission measures of effectiveness (MOEs). Finer-grained processing of relevant exercise data than has been used in previous analysis techniques results in hundredfold increases in sample sizes; this in turn improves the statistical significance and accuracy of the estimated MOPs and MOEs. DREV model-based measures (MBMs) use simple decision models to assess the value, usefulness or goodness of the picture a commander uses for a decision or a mission. The results from two versions of DREV MBMs are compared.

## RÉSUMÉ

Les résultats d'analyses présentés découlent de l'application des nouvelles méthodes du CRDV pour étudier, analyser et évaluer la valeur, l'utilité ou la bonne qualité de l'information tactique utilisée par les commandants dans leur processus de décision et particulièrement pour supporter le ciblage au-delà de l'horizon de ses propres capteurs. Ces méthodes lient la qualité de l'information ou les mesures de performance des systèmes (MDP) aux mesures d'efficacité (MDE) des décisions prises ou des missions en jeu. Un traitement plus fin de toute l'information pertinente d'un exercice militaire permet d'obtenir des échantillons dont la taille est accrue par un facteur de l'ordre du centuple, ce qui a pour effet d'améliorer la signification statistique et la précision des MDP et MDE estimées. Les nouvelles mesures, basées sur des modèles (MBM), utilisent des modèles décisionnels pour déterminer la valeur, l'utilité ou la bonne qualité de l'image tactique des systèmes embarqués qui traitent l'information maritime utilisée par un commandant pour une décision ou une mission. Les résultats de deux versions des MBMs du CRDV sont comparés.

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## EXECUTIVE SUMMARY

Developing, managing and sharing a common tactical picture is of crucial importance to all military operations, and extended-range anti-ship missiles and over-the-horizon sensors that support over-the-horizon targeting (OTH-T) now impose particularly demanding requirements for a wide-area picture (WAP) in the maritime environment. Producing and sharing a common recognized maritime picture (RMP) of high enough quality to sustain effective military operations is thus one of the Canadian Navy's top priorities.

In the past, the effect of improvements or changes to communications, command, control and information system (C3IS) on military operations or mission effectiveness has been evaluated through the measurement of system performance and information quality quantities known as measures of performance (MOPs). The results fall short of demonstrating clearly the impact of C3IS improvements or changes on the capability to conduct successful operations or on mission effectiveness, quantities defined here as measures of effectiveness (MOEs). In fact, one must relate information quality and system MOPs to decision and mission MOEs in a causal manner; only by doing so can one establish the usefulness or goodness of the RMP tactical information used by a commander to plan operations and make decisions.

DREV undertook the development of new measures as the Canadian contribution to the AUS-CAN-NZ-UK-US Ad Hoc Working Group on the "Management of Organic and Non-organic Information in a Maritime Environment" (MONIME), proposing new methods to study, analyze and assess the value, usefulness or goodness of the information and systems used by commanders in decision making. The new methods provide insights not available using MONIME's current methods for analyzing a series of live or simulated exercises. Finer-grained processing of the raw data from MONIME studies results in a hundredfold increase in sample sizes, thus improving statistical significance and the accuracy of MOP and MOE estimates. The new DREV MBMs were presented in a previous document; here we show how they assess the value, usefulness or goodness of the picture a commander uses for decisions or missions during a specific exercise.

The MBMs are used to assess the data collected during the TIMSIM '93 military exercise, focusing on afloat command information system capabilities in support of over-the-horizon targeting. The results assess the value of the information made available to a commander by considering each tactical report of track data that meets a given set of engagement conditions. Locational, systems and temporal data contained in reports are used to establish possible engagement parameters and scenarios, and outcomes subsequent to all decisions that are feasible at that moment are assessed using decision-process model definitions and algorithms that include hit-probability calculations using ground-truth information (since this is a post-exercise analysis). Appropriate areas of uncertainty are used to represent the intrinsic level of uncertainty of missile-interception areas, ground-truth data and the information presented by C3I systems to commanders. The measures include reward values that are based on the allegiances of contacts in the weapon impact area.

The results from the new MBMs are also compared with those obtained with a previous version that did not consider the cost of firing a weapon.

## 1 INTRODUCTION

Providing accurate estimates of the value, usefulness or goodness of information for productive, successful decision making or mission planning requires that the effects of changes in tactical information systems and procedures on mission effectiveness be determined. Meeting this difficult requirement is an important step in the cost-effective development and integration of systems to support military operations, and the assessment of man-in-the-loop systems holds the greatest potential to impact the effectiveness of our forces.

Improvements to wide-area naval tactical picture (WANTAP) systems, procedures and standards for afloat commanders have been driven by the need for joint and coalition operations over wide geographical areas under complex geopolitical scenarios. Extended range anti-ship missiles and over-the-horizon sensors that support over-the-horizon targeting (OTH-T) now lead to requirements for a wide-area picture (WAP), in geopolitical situations now more complex than those of the cold war. The DREV Work Unit "Data fusion rules" was established to address the requirement deficiencies implied by these new "millennium" missions and theaters, which both sea- and shore-based national systems must support.

This Work Unit is based upon work done in an AUS-CAN-NZ-UK-US C3 (command, control and communications) Organization (Refs. 1, 2) work program under an ad-hoc working group (AHWG) investigating the management of maritime information. Results and data from a series of experiments for analyzing WANTAP systems conducted by the AHWG are used to evaluate the new measures developed by DREV for assessing the impact of system changes on mission effectiveness. The AUS-CAN-NZ-UK-US C3 Organization's "Handbook 5 (HB5) Guidelines for Maritime Information Management" (guidelines for the procurement of national C3I WANTAP-based systems for compiling and sharing accurate WAPs) (Refs. 2, 3), a compendium of the findings and recommendations from these experiments, is used in these studies.

The new model-based measures (MBMs) developed by Defence Research Establishment Valcartier (DREV) were designed to improve the accuracy of estimates

of the effect of information quality and systems performance on mission effectiveness through the application of a set of decision models and utility functions. Traditional evaluation methodologies reach conclusions by examining the consequences of each decision actually taken during an exercise or simulated engagement. Realistically, very few significant decisions can actually be taken under such conditions, so conclusions must be based on very sparse data. The new DREV methodology extends the statistical base by considering not only decisions that are actually made but also those that *might* have been made, based upon the information available to the commander at the time. By modeling all potential engagements, with due consideration to the errors and uncertainties that constrain them, the DREV approach provides a much firmer statistical foundation for the evaluation of the components of maritime command and control systems than do the methodologies heretofore used.

These decision models and MBMs were reported by the authors in Ref. 4, but a summary is presented here in support of the new material of this report. Two software implementations of these measures were implemented to assess engagement opportunities in OTH-T scenarios so to reflect the expected outcome of eventual engagement operations using WANTAPs, and the usefulness of these software tools for investigating the impact of WANTAP picture quality and system performance on command and control effectiveness was assessed.

This document presents analysis results of the application of DREV's MBM implementations to the 1993 Tactical Information Management Simulation (TIMSIM '93) data (Refs. 5, 6). Actual models are presented in Refs. 4, 7. More detailed information concerning a previous version of the models, along with the computer implementation, data characterization, preprocessing and earlier TIMSIM '93 data analyses performed with that version are described in Ref. 5. The new round of analyses discussed here was performed in order to upgrade and validate previous conclusions using a newer and better-tuned model implementation whose latest updates are documented in Refs. 4, 6-8. Other experimental data from naval exercises (Refs. 9-11), such as the Rim of the Pacific 1996 live exercise (RIMPAC '96), have not yet been processed using the DREV models, but results from analyses of these experiments are used to validate the proposed methodology.

Background information on the selected DREV MBMs and the general set-up used to analyze live or simulated military exercises are presented in Chapter 2. Descriptions of the processing applied to the output of the models are given in Chapter 3. Chapter 4 describes supplementary analyses that were performed. The results are discussed in Chapter 5. Interpretation of the model-based measure values and conclusions are presented in Chapters 6 and 7 respectively. A glossary, a list of acronyms and abbreviations, and summary tables of the analysis results make up the Appendices.

This work was performed at DREV between May 1995 and June 1998 under Work Unit 1ba16: "Data Fusion Rules."

## **2 MODEL-BASED MEASURES AND ANALYSIS SET-UP**

The analyses performed are based on the decision models for the assessment of engagement opportunities defined in Refs. 4-7, 12, using the computer implementation described in Refs. 5, 6. In addition, this document includes several results that were gathered in a previous round of analyses using supplementary analysis programs (see Refs. 5, 6, 8), which are not part of the models as such but yield insightful complementary information on delays and positional errors.

### **2.1 Summary of Model-based Measures**

Essential information and definitions needed to understand the parameters used in the analysis set-up are presented in the following sub-sections. Most of this material is addressed in more detail in Ref. 4.

#### **2.1.1 Engagement Situation**

Ships within an area of operational interest (AOI) displayed by a WANTAP system can be classified according to their perceived or reported allegiance as friendly (F), hostile (H), neutral (N) or of unknown allegiance (U), a subset of NATO-assigned allegiances. Friendly and hostile ships are military vessels of the forces in conflict. Usually those whose allegiance is F are referred to as the "blue" force and those whose allegiance is H as the "orange" or "red" force. Neutral ships—usually merchant ships, liners or other vessels extraneous to the conflict—are often represented as "green." The allegiance "unknown" indicates a lack of information about a contact, and "white" is used to indicate such pending tracks. A perfect reporting system with all the appropriate information would not need this classification. Only F, H and N allegiances appear in the ground-truth (GT).

In our models, an engagement situation occurs every time an armed ship from the blue force has knowledge of the presence of an enemy ship (orange force) within range of its weapons. A typical such situation occurs every time the commander of an armed ship (CS) selects, for the next engagement, an intended hostile (IH) target from those displayed by the CS tactical system. We assume that the

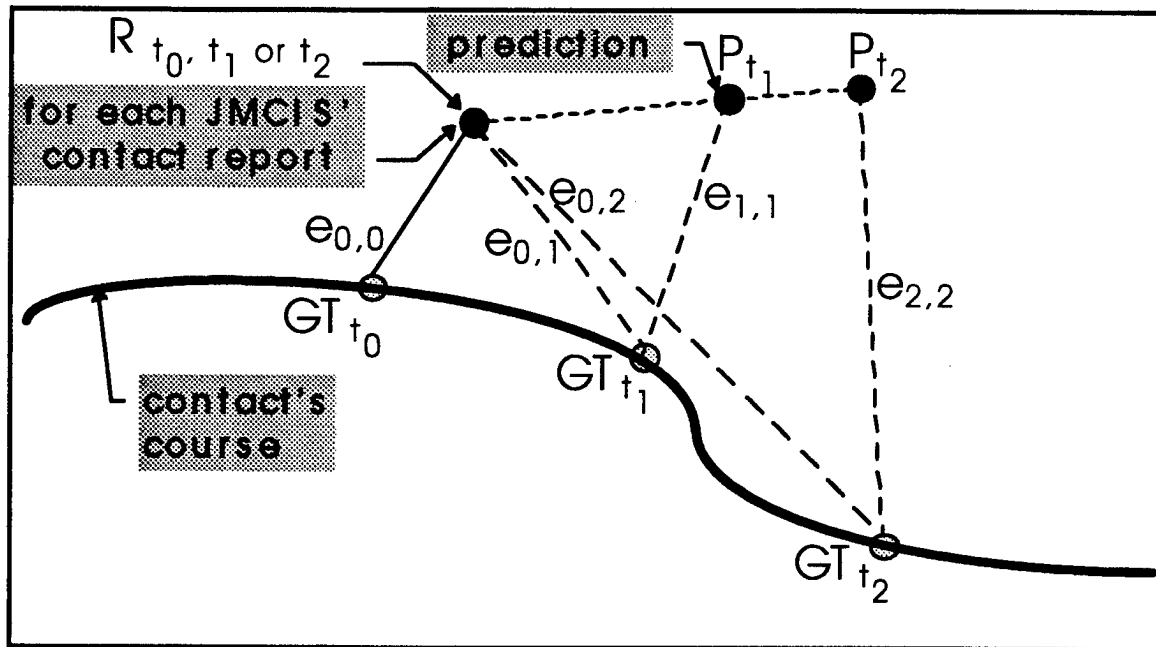


FIGURE 1 - Positional errors with and without prediction relative to GT positions at three times

commander follows appropriate procedures, that the target is located within the physical boundaries that limit the systems (weapons, sensors, information and command) available to the CS and that it can be engaged under the rules of engagement (ROEs) in effect at that time.

#### 2.1.1.1 Contact Information Reports

The tactical information about a ship forwarded to a CS through different information channels and means contains the identification (class-name) of the ship, its position and, eventually, other information such as course, speed and allegiance. Each occurrence of such combined data is referred to as an information report on a contact. The "position time"  $t_{pos}$  ( $t_0$  in Fig. 1) indicates the time at which the information was acquired (sensor time). The "report time"  $t_r$  ( $t_1$  in Fig. 1) is the time when the information report was made available to its recipient's database. In a real situation another time may be necessary: the commander's decision time ( $t_2$  in Fig. 1), which occurs after  $t_1$ . Figure 1 shows a first-order position prediction algorithm such as dead reckoning (DR), with the reported

position at  $t_0$ , the predicted positions at  $t_1$  and  $t_2$ , and the GT positions at  $t_0$ ,  $t_1$  and  $t_2$ . With respect to the preceding definition of contact reports, we can consider that an engagement situation occurs each time the commander of an armed ship from the blue force receives an information report on a presumably hostile contact. For the MBMs, hostility depends on class-name identification or allegiance as indicated in the information report.

### 2.1.2 Ground Truth

An ultimate goal in C3I is to share the same WANTAP simultaneously by all units of a battle force<sup>1</sup>. In real systems, however, the WANTAP view or tactical information available to commanders may be incomplete, erroneous and cluttered with duplicated information. In contrast to this partial or incorrect view there is, of course, only one actual wide-area naval situation at any given time: the ground truth or GT. GT information consists of identification and allegiance of each ship, along with its location (speed and course may be included or can be estimated from the sequence of position values in the GT) at any given time<sup>2</sup> for the entire area to be controlled by a force over the period of time considered. Thus, the GT WAP can be viewed as a list of position reports across a time scale and a geographical area with the required granularity. If necessary, it can be reconstructed by combining all the information collected during a life exercise, but a reconstructed GT is not as complete and accurate as one used to drive a simulated exercise (see GT error rate in Refs. 9, 10).

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<sup>1</sup> This view was originally defined by the Canadian Navy as the common Recognized Maritime Picture (RMP), but in HB5 it is now defined as the Maritime Tactical Picture (MTP): the global picture.

<sup>2</sup> In practice, the GT data may be listed according to a discrete time variable with short steps, often one minute.

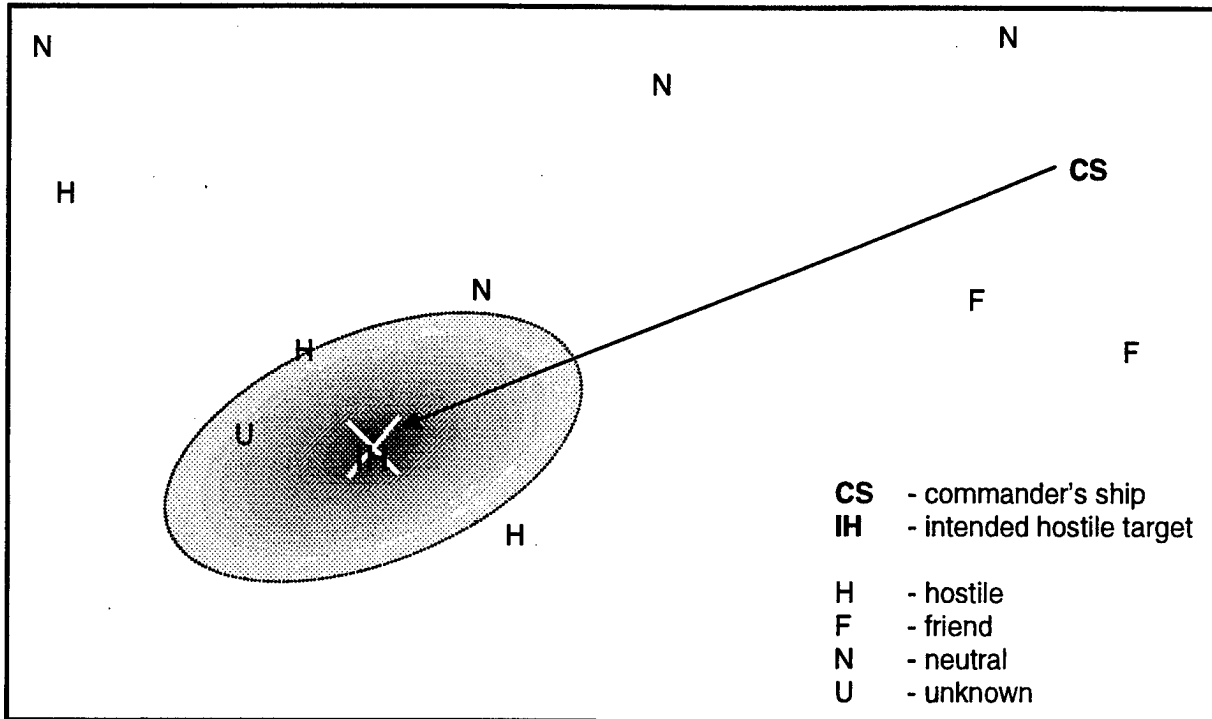


FIGURE 2 - A typical engagement situation with a weapon aiming vector and a weapon-uncertainty area centered at the intended hostile (IH)'s position

### 2.1.3 Positional Uncertainty

The positional information in WANTAP systems is uncertain for a number of reasons. This lack of precision is expressed by an area-of-uncertainty (AOU): there is a probability  $p_i$  that the object lies anywhere within this area and a probability  $p_o = 1 - p_i$  that it lies outside. Typically, a system may use a confidence level of 95%; that is, the probability of the object being outside by *chance only* is 0.05. In some systems the contact AOU is provided by the source of data, but since this information is not available for all the contact reports used in our analysis, we have simplified the computation by assuming that  $p_o$  is null or negligible (i.e.,  $p_i = 1$ ).

### 2.1.3.1 Weapon-uncertainty Area

In DREV MBMs the weapon-uncertainty area (WUA), also called the weapon footprint, is modeled as an ellipse centered on the location at which the weapon is aimed. Its orientation, i.e., its major axis, lies along a straight line connecting the weapon-launching ship to the presumed location of the intended target (see Fig. 2). The WUA is specified by three parameters :

1. the half-length of the minor axis of the ellipse ;
2. the half-length of the major axis of the ellipse; and
3. a weight function defined over the area of the ellipse.

The weight function, defined over all points within the elliptic area (Fig. 2), assigns to each such point a weight indicating the likelihood of that point's being hit by the weapon if it is launched. Any suitable function can be used for this parameter.

The scenario of Fig. 2 can be modified if it is assumed that the commander uses predicted positions, which may be calculated by his information systems. Then at  $t_1$  instead of using the report at time  $t_1$  ( $R_{t_1}$ ) of Fig. 1, he uses the predicted position at time  $t_1$  ( $P_{t_1}$ ). This new scenario with the predicted position of the intended hostile (IH-P) is shown in Fig. 3.

### 2.1.3.2 Circular-uncertainty Area

A circular-uncertainty area (CUA) represents a possible positional error in a contact information report from a given WANTAP system. The CUA, which is equivalent to the AOU of the specified contact information report, must be applied to all the GT positional reports used to assess a given measure at decision time. Figure 4 shows a CUA for each GT position at a given time—except for the commander's ship, which is used as a reference. The CS displayed information may not contain any data for a given GT position or it may display "phantom" ships. The displayed data may also contain other errors—in type of contact or allegiance, for example.

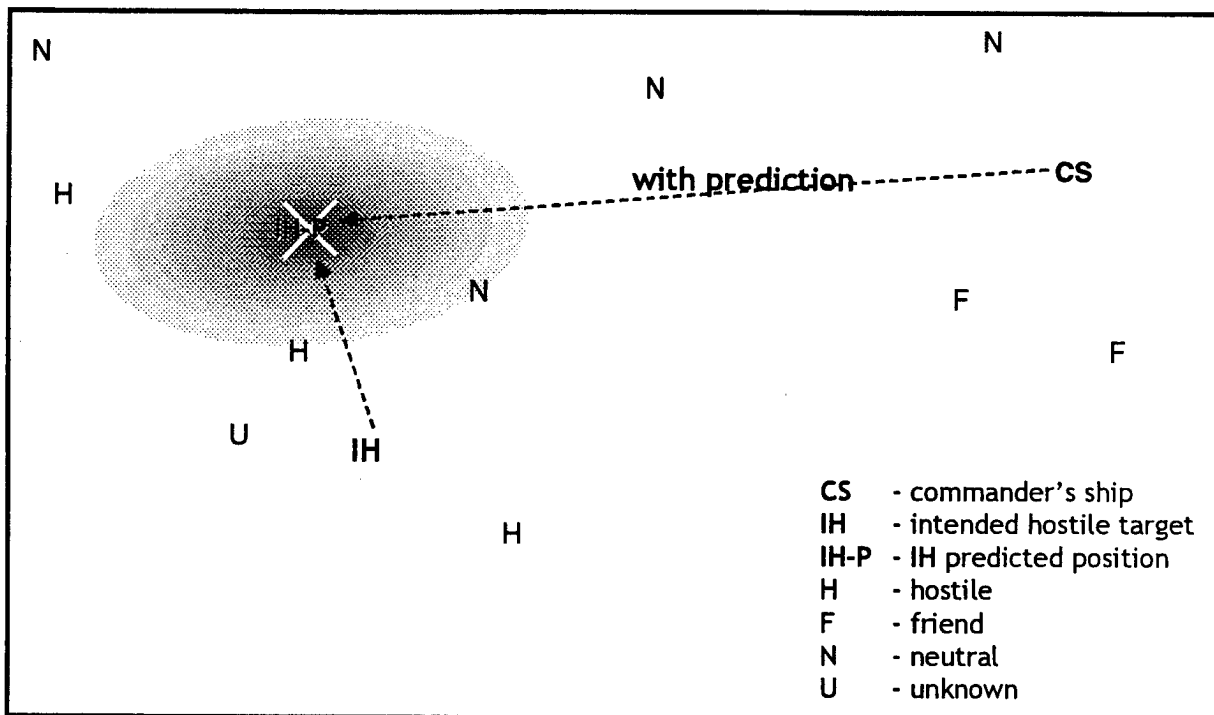


FIGURE 3 - A typical engagement situation with a weapon aiming vector and a weapon-uncertainty area centered at the IH-P's position

Within the models, a CUA is specified by two parameters:

1. a circle radius; and
2. a probability distribution function (pdf) over the circular area.

The pdf parameter is a probability density function defined over all points within the circle. It assigns to each point a probability that the ship (if there is one) corresponding to the contact information report is at that point at the position time indicated in the report (or at a later time, to include the effect of delay on this probability). Although any bidimensional pdf can be used for this parameter, we use uniform, Gaussian and triangular bivariate distributions as starting points, as described in the next subsection. The Gaussian bivariate pdf is defined over the entire plane, so a truncated version—one with a zero value outside the CUA (Ref. 4)—is used to reduce the computation load.

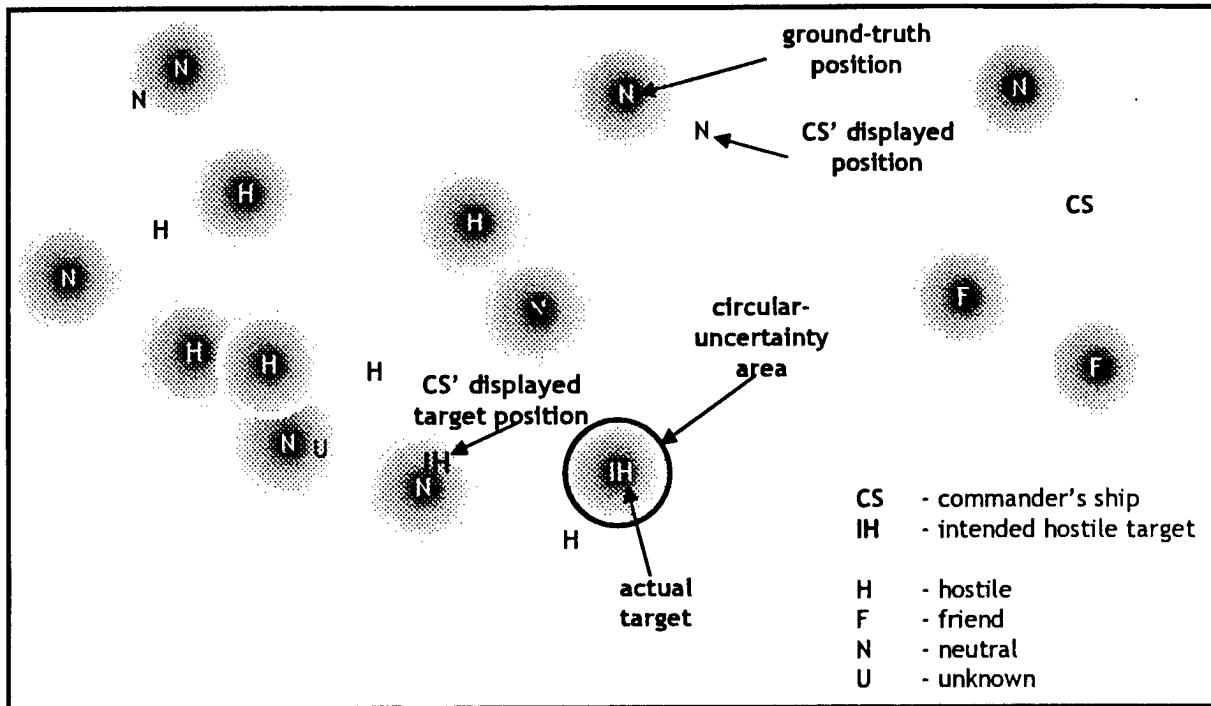


FIGURE 4 - A CUA is applied to each GT position, except for the reference ship

A CUA can be assigned to any contact, but in the particular case of a presumed hostile contact we call it instead a target-uncertainty area<sup>3</sup> (TUA), since we are primarily concerned with the impact and outcome of engagement decisions concerning contacts of this type.

The CUA represents not only the expected errors found in operational systems but also errors within GT position reports. It has been observed (Refs. 9, 10) that even in controlled experiments proper GT data files may have to be reconstructed from partial information: holes in the GT data may have been filled by interpolation that introduces positional imprecision. In some cases, parts of the GT files may even be reconstructed using contact information reports from a commander's database. In addition, it cannot be assumed that all positions in WANTAP contact information reports are matched by equivalent GT position reports at the exact same times. In such cases we have to interpolate between two GT position

<sup>3</sup> In Ref. 5, we do not use the TUA acronym and refer only to the more general CUA.

reports to get the equivalent GT position at a particular time. All these considerations can be combined in the view that a CUA around any GT position report represents a combination of all the errors in both the CS contact information and GT position reports. This greatly simplifies the computation required for each MBM.

Finally, we will later show (Section 3.6) that considering CUAs around GT positions accounts for all possible WUA center-position alignments within a given TUA (the CUA of a target). The uncertainty of the TUA is therefore transferred and blended into an equivalent positional uncertainty around the GT location values in the vicinity of the WUA. This allows computations in the models to use a single WUA for a given target and still accounts for all the uncertainty involved.

#### **2.1.4 Engagement-opportunity Reference Times**

The previous section defined an engagement situation as occurring whenever the commander of an armed blue ship receives an information report on a presumed hostile contact. That information report includes a position time  $t_0$  and a report time  $t_1$ , with  $t_0 \leq t_1$ . The models we propose may use either of these two time values as the actual time of engagement opportunity, i.e., the time at which an engagement might take place (or might have occurred). Of course, in reality, an engagement decision cannot be taken before the existence of the information report is known. However, allowing the selection of different times of engagement in the models yields essential measures for estimating the impact of system changes on mission effectiveness.

#### **2.1.5 Measures of Engagement Opportunities**

In geopolitical conflicts where engagement situations may arise, it is of crucial importance to evaluate the impact of an offensive action such as the launch of a weapon. This impact may be evaluated according to many parameters and from many different points of view: for example, the cost and effort of conducting an offensive action, expected enemy damage as a result of such action, tactical consequences, and geopolitical and other aspects. Obviously, the impact is not necessarily the same for the personnel aboard a ship under threat in a short-range encounter as it is for the fleet commander or the government of the nation under

whose flag the ship sails. It is thus unreasonable to hope to identify a simple measure of impact that would apply to all cases of interest, but it is surely possible to capture an essential component of that impact by establishing some quantification of the outcome of an offensive action. Two measures are proposed here for this purpose: the "pertinence-of-engagement" and the "intended-target-opportunity." Their descriptions follow.

#### **2.1.5.1 Pertinence-of-engagement Measure**

The pertinence-of-engagement (POE) measure is a means to assess the general outcome of launching a weapon at a target in an engagement situation. It can be viewed as a measure of the pertinence of the decision to engage. It involves three aspects:

1. The cost<sup>4</sup>-of-firing (COF) the weapon: a negative quantity expressing the expense (economic, material and personnel) associated with the launch of the weapon.
2. The hit probability<sup>5</sup> (HP): the probability that the weapon will hit something (a ship) within its WUA. It is computed by looking at the joint-probability distribution of all the ships whose CUA intersects the WUA at the time of engagement opportunity (see Ref. 5 for precise mathematical formulations and computing algorithms).

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<sup>4</sup> In this context the cost is taken in its mathematical sense, i.e., a utility function/value, as is commonly used in mathematical models.

<sup>5</sup> In Ref. 5 two different hit probabilities are defined: the General Hit Probability (GHP) and the Specific Hit Probability (SHP). It has been observed that this technique could lead to unrealistic assessments of outcomes in some cases, i.e., when the CUA of the intended target does not intersect the WUA, and hence its SHP is 0, while the CUAs of a number of friendly or neutral ships *do* intersect it. The models now consider only the GHP (called simply HP). The probability of hitting a specific ship is still computed and available within the models, but it is integrated in the reward-value terms of the equations to avoid the absorbing effect of multiplying by a zero value, thus preserving the continuity of the measures.

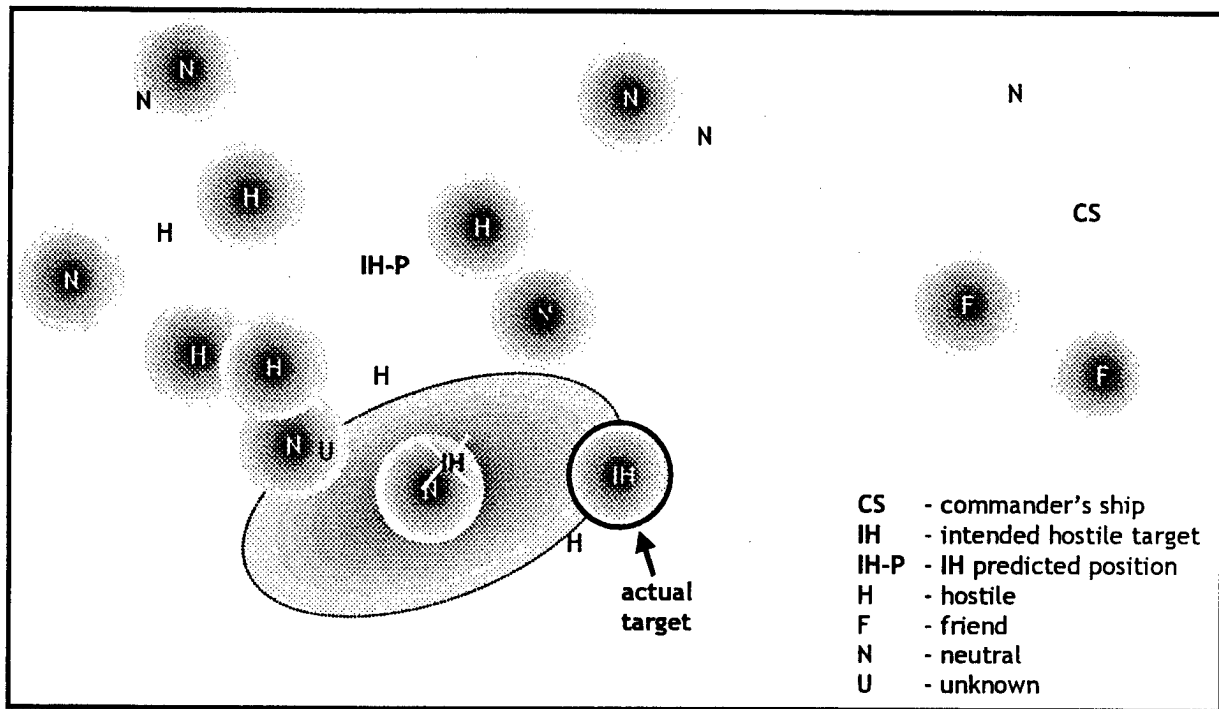


FIGURE 5 - Intersections of three CUAs with the WUA: surface overlaps

3. The pertinence-reward-value<sup>6</sup> (PRV), which combines the allegiances of the potential target ships with their probability of actually being hit should the weapon be fired, for all ships within the WUA at the time of the engagement. See Ref. 12 for explanations and Refs. 5, 6 for the precise mathematical formulations and computing algorithms.

Figure 5 shows the CS aiming at the last reported position of the intended hostile (IH) target. Black text symbols represent what is shown on the CS tactical display and white text symbols, with their surrounding CUAs, represent the actual GT positions of ships superimposed over the CS tactical display area at the same time. A MBM hit probability is defined by the joint probability distribution of all ships whose CUA intersects the WUA; e.g., the surface overlaps of two N GT and the IH GT CUAs in the snapshot shown in Fig. 5.

<sup>6</sup> The PRV is equivalent to the General Reward Value (GRV) in Ref. 5.

### 2.1.5.2 Intended-target-opportunity Measure

Though quite similar to the POE measure, the intended-target-opportunity (ITO) measure is more specific because it focuses on the outcome of launching the weapon with respect to the intended target in the engagement situation. It involves:

1. The COF (as defined previously),
2. the HP (as defined previously) and
3. the target-reward-value<sup>7</sup> (TRV), which combines the allegiances of ships with their probability of actually being hit, should the weapon be fired, for all the ships within the WUA at the time of the engagement opportunity. It is similar to the PRV, except that it gives lower weight to hostile ships other than the intended target (see Ref. 12 for explanations and Refs. 5, 6 for the precise mathematical formulations and computing algorithms).

### 2.1.6 Model-based Measures

The various combinations of the two measures of engagement opportunities with the time at which engagement might take place lead us to consider six different models for the assessment of engagement opportunities. Each provides a numerical measure that assesses the outcome of an offensive action, i.e., launching a weapon, under a certain point of view (POE or ITO measure) and in a certain situation (time of engagement opportunity with and without positional prediction<sup>8</sup>).

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<sup>7</sup> The TRV is equivalent to the Specific Reward value (SRV) in Ref. 5

<sup>8</sup> Algorithms such as dead-reckoning (DR) estimation are commonly used as navigation aids. First-order DR estimates the position of a moving body from the last values of its reported position and velocity vector. Higher-order DR uses other information such as displacement influences and angular accelerations.

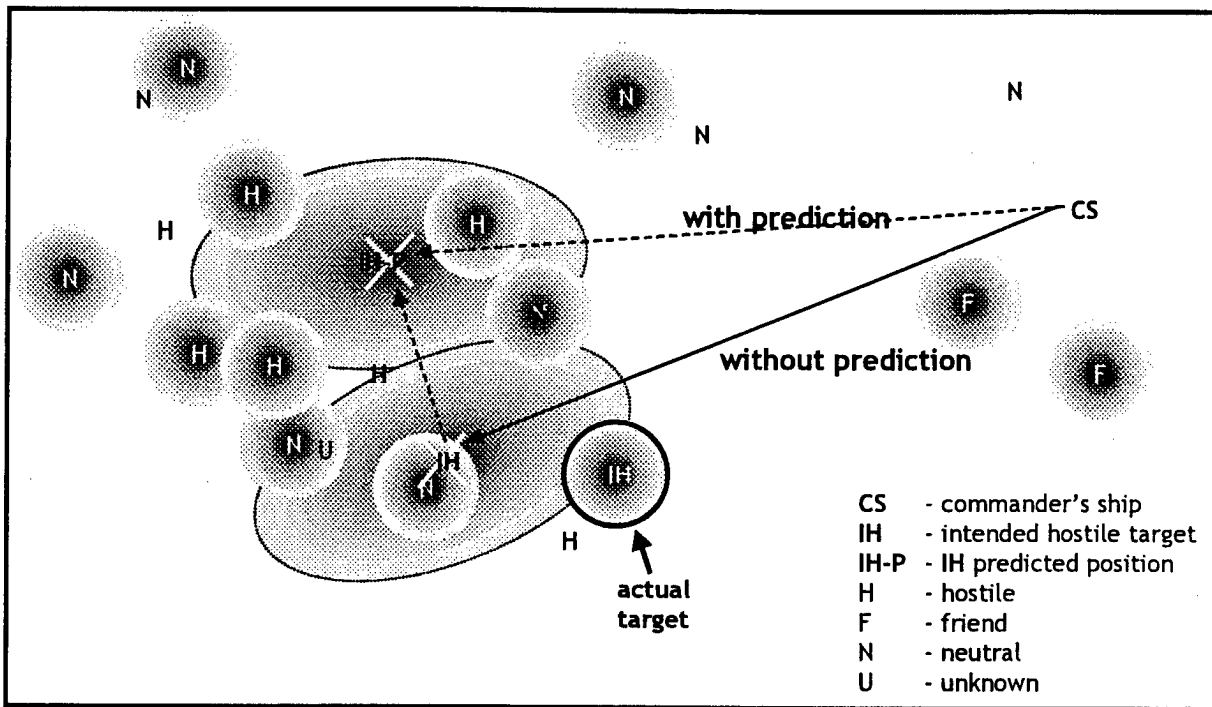


FIGURE 6 - CS display of two possible positions of the intended target

These measures causally<sup>9</sup> determine the impact of information lacks and system limitations on mission effectiveness.

Figure 6 shows a possible set of engagement conditions for two target-position values displayed to the commander: with and without positional prediction. The positional prediction illustrated is first-order dead reckoning, which assumes constant speed, no change of heading and no secondary effects such as variations caused by wind or water currents. MBMs can assess different hit probabilities even when the information displayed to the CS is produced using different techniques and processing algorithms.

<sup>9</sup> In causal analysis, the probable causes of observed events (a productive hit of a hostile ship or a counter-productive hit of a friendly ship) are traced, while causality is a relation between simple results and the state of the world. This includes environment, platforms, information quality and system states. Here, it is more a question of correlation between the result of a decision and the quality of information as well as the performance of the systems involved in the closed-loop scheme of command and control.

**2.1.6.1 Model 1 - Pertinence-of-engagement without Delay**

The "pertinence-of-engagement without delay" model assumes no delay between the time the information is acquired by the sensor, acquisition device or mechanism and the time this information is made available as an information report to the commander of each blue ship. That is, we assume that position time is equal to report time and that the engagement might have taken place at position time. With respect to information degradation over time, the "ideal-engagement-situation" (IES) model serves a standard to compare other models with. The POE measure output of the model is defined as a POE-optimal (POE-O) measure, and IES POE-O measures can be used as a baseline to assess the dependence of alternate engagement situations on system performance. This is the "sensor" baseline, since the systems primarily involved are the sensors themselves with their geo-referenced results; other systems have not yet had the opportunity to affect the value of reports for decision making.

**2.1.6.2 Model 2 - Pertinence-of-engagement with Delay and without Prediction**

The "pertinence-of-engagement with delay and without prediction" model assumes that an engagement may take place only at report time (with report time > position time). It can be applied to each engagement opportunity. The resulting measure is defined as a POE-delay (POE-D) measure, indicating a delay between information acquisition and the occurrence of the engagement situation. The information is not updated during this delay and the target location used is the location recorded at position time, so the model deals with a time-degraded tactical picture.

**2.1.6.3 Model 3 - Pertinence-of-engagement with Delay and Prediction**

Like the previous measure, the "pertinence-of-engagement with delay and prediction" model also outputs a POE value: a POE-delay-prediction (POE-D-P) measure. It assumes that engagement may take place only at report time (with report time > position time), but allows for the use of some means to extrapolate or

predict a new target location at the time of engagement opportunity. In this model, the weapon is aimed at the predicted location of the target at report time.

#### **2.1.6.4 Model 4 - Intended-target-opportunity without Delay**

The "intended-target-opportunity without delay" model is similar to Model 1, except that it outputs an ITO measure, defined as an ITO-optimal (ITO-O) measure, instead of a POE-O measure. Compared to the POE measure, the ITO measure assigns a lower reward value for damaging an enemy ship that is not the intended target.

#### **2.1.6.5 Model 5 - Intended-target-opportunity with Delay and without Prediction**

The "intended-target-opportunity with delay and without prediction" model is similar to Model 2, except that it outputs an ITO measure, defined as an ITO-delay (ITO-D) measure, instead of a POE-D measure.

#### **2.1.6.6 Model 6 - Intended-target-opportunity with Delay and Prediction**

The "intended-target-opportunity with delay and prediction" model is similar to Model 3, except that it outputs an ITO measure and is defined as an ITO-delay-prediction (ITO-D-P) measure, instead of a POE-D-P measure using the predicted position at the WANTAP report time.

### **2.1.7 Meaning and Usefulness of these Models**

Models 1 and 4 may be viewed as "optimal" models since they are equivalent to assuming that information reports are available instantaneously, as soon as information is gathered by sensors or acquisition devices or mechanisms (i.e., position time = report time = time of engagement opportunity). These models deliver the maximum usefulness value of the information that can be provided to a commander. This value is the source or sensor baseline that can be used to compare the impact of changes to system architecture on mission effectiveness.

Models 2 and 5 are "time degraded" models in which target information has not been updated since position time (i.e., position time < report time = time of engagement opportunity)<sup>10</sup>. Time degradation of the information represents system limitations that are assumed to imply sub-optimal performance.

Models 3 and 6 are "predictive" models in the sense that they try to compensate for time degradation by updating information according to a prediction algorithm. Any prediction scheme can be fitted into these models. Comparing the results obtained using these models to those obtained using "time degraded" models (i.e., Models 2 and 5) may be helpful in order to estimate the quality of a given predictive algorithm and to assess its impact on mission effectiveness. As a starting point, we use a predictive algorithm that assumes dead-reckoning<sup>11</sup> of target ships.

Models 2 and 5 and Models 3 and 6 can be extended to become Models 2\* and 5\* and Models 3\* and 6\* by taking into account the time a commander takes to deliberate and to reach a decision, at time  $t_2$  in Fig. 1. Models 1 and 4 use<sup>12</sup>  $t_0$ , Models 2 and 5 and Models 3 and 6 use  $t_1$  and Models 2\* and 5\* and Models 3\* and 6\* use the third time:  $t_2 \geq t_1 \geq t_0$ . The differences between the results from these models can be used in the relative assessment of the role of the human in the decision process or in the information and other systems involved. Such assessments can be used in training to compare and rank the performance of decision makers (this extension has not yet been done but is planned as a future exploitation of DREV MBMs).

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<sup>10</sup> The position time or sensor detection time is earlier than the report time. We set the time of an engagement to the report time so as to measure the data-aging effect on the result of the engagement.

<sup>11</sup> Dead-reckoning, "the determining of the position of a vehicle at one time with respect to its position at a different time by application of vectors representing courses and distances", Ref. 13.

<sup>12</sup> The sensor time  $t_0$  is the same for any model for a given report. The other times,  $t_1$  and  $t_2$ , are the same for the various models as long as they refer to the same database and report. For the same report but from a different database, e.g., for another ship,  $t_1$  and  $t_2$  may be different.

The decision rule conveyed within these models is implicit, since the output measure (POE or ITO) is a direct assertion about the outcome of a commander's engagement decision. The actual range of values taken by the POE and ITO measures is implementation-dependent (according to the values set for allegiance factors in the PRV or TRV and the utility imposed by the COF) but it is a continuous interval from a lower bound indicating the worst possible outcome to an upper bound indicating the best. From the point of view of the commander of a blue force ship, the worst possible outcome of an engagement is a sure hit on a friendly or neutral platform. The best outcome is a sure hit on the intended hostile target or on any hostile target.

The following results are based on the application of "Configuration 4" (Ref. 4): Multiple engagements/multiple models. Two or more models are selected and applied concurrently over a series of engagement situations, thus allowing a comparative analysis of WANTAP system results from any sample of engagement situations. Conclusions drawn from an analysis with this configuration are statistically significant when the sample size is large enough, say in excess of one hundred.

This technique can be used effectively to assess the impact of the delay between information acquisition and information availability (the difference between the position time and the report time in the contact information reports), of the use of position-prediction algorithms on engagement outcomes and of system and information changes on the quality of decisions and on mission effectiveness. This is achieved by concurrent applications of POE models (Models 1, 2 and 3) and/or ITO models (Models 4, 5 and 6) over the same engagement situation (or the same set of engagement situations) and comparative evaluation of the output measures.

In the analyses, the set of scenarios is applied consecutively to large samples of engagement situations from a simulation experiment (TIMSIM '93). Actual engagement decisions are relatively few in such experiments (as they should be in live or simulation exercises) so the conclusions drawn from their outcomes have very poor, if any, statistical significance. In contrast, applying the models as we did over the experiment data yields samples of sizes approximately a hundredfold larger, which strengthens the statistical soundness of the inferences drawn. During

the four days of this exercise we observed 33 qualified engagements, as compared to 3882 MBM-simulated ones for the Force Over-the-horizon Track Coordinator (FOTC) alone, a factor of 117 (for more information about this aspect see Refs. 5, 12, 14, 15).

## 2.2 Analysis Set-up

The analyses performed are based on the decision models for the assessment of engagement opportunities defined in Ref. 4 and summarized above. We assume a memory-less decision-action scheme scenario that jumps from one engagement opportunity to the next.

In a closed-loop simulation, sequential events would affect future events and another module would have to be added to the current implementation of the MBMs, or in the determination of the value of information in decision making, to assess the damage to a target given a particular engagement outcome or after one or several hits to a contact.

Here we focus on the memory-less case and assume that joint probabilities of WUA and CUA intersections are found using numerical techniques, either brute-force Monte Carlo or integral approximations. We used the computer implementation of the MBMs as described in Refs. 5, 6. In addition, this document includes several results that were gathered in a previous round of analyses using supplementary analysis programs that are not part of the models as such, but yield complementary information on delays and position errors.

The decision models were set up in an analysis framework consisting of several simulation runs according to a number of different scenarios. With respect to the six MBM decision models, each simulation run applies two models—Models 1 and 4, Models 2 and 5 or Models 3 and 6—to the same set of data. Each run outputs both the pertinence-of-engagement (POE) measure and the intended-target-opportunity (ITO) measure for an otherwise identical model set-up for delay and prediction. Each run processes a data set consisting of the ground-truth (GT) data for one day of the TIMSIM '93 simulation and the data from one WAPS (wide-area

**TABLE I**  
**Data sets used in the DREV MBM demonstration**

data set number	WAP node	day identification	source or remote (OTCIXS <sup>14</sup> /HIT <sup>15</sup> )
1	FOTC	1	source
2	TWCS	1	source
3	SAG1	1	OTCIXS
4	SAG2	1	HIT (75 or 300 b/s)
5	FOTC	2	source
6	TWCS	2	source
7	SAG1	2	OTCIXS
8	SAG2	2	HIT (300 b/s)
9	FOTC	3	source
10	TWCS	3	source
11	SAG1	3	OTCIXS
12	SAG2	3	HIT (75 b/s)
13	FOTC	4	source
14	TWCS	4	source
15	SAG1	4	OTCIXS
16	SAG2	4	HIT (300 b/s)

picture systems such as JOTS, TWCS, JMCIS and GCCS)<sup>13</sup> for that day; applying the models in the multiple engagements/multiple models configuration for each run. Thus, four days of TIMSIM '93 data yield 16 distinct data sets as identified in Table 1.

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<sup>13</sup> The Joint Operational and Tactical System, Tomahawk Weapons Control System, Joint Maritime Command Information System, and Global Command and Control System respectively.

<sup>14</sup> The OTCIXS, Officer in Tactical Command Information Exchange System, or ACIXS, Allied Command Information Exchange System, is a communications systems that uses satellite technologies at data rates ranging from 2 400 to 9 400 kb/s. TADIXS, Tactical Data Information Exchange System, is the real system (UHF SATCOM data link) and OTCIXS or ACIXS is a concept.

**TABLE II**  
**Mapping of the (16X6) 96 distinct model outputs**

decision time	position	POE	ITO
no delay	reported	Model 1	Model 4
with delay	reported	Model 2	Model 5
with delay	predicted	Model 3	Model 6

In this context the FOTC compiles the tactical track data (manages the surface, sub-surface and air tracks) and sends its tactical picture to two Surface Action Groups (SAG1 and SAG2). The TWCS performs a similar information-management function and tactical-picture compilation tailored to the needs of OTH-T, since it is a weapon control station for this purpose.

In the Day 1 and 2 results of Table I the hostile forces were cooperative; that is, they used active devices such as radar and radios. On the other days they were non-cooperative.

Three simulation scenarios were executed for each of these data sets, corresponding to the three pairs of applied decision models. Consequently we obtained a total of 48 different simulation runs with 96 distinct model outputs, 48 POE and 48 ITO sets of results. These scenarios and model numbers are mapped in Table II.

Each run used an identical set of simulation parameters, shown in Table III. All the engagement situations occurring in the WAPS data were processed concurrently according to the two models specified by the scenario; i.e., POE and ITO measures were computed for each of these engagement situations.

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<sup>15</sup> The HIT, high interest track, broadcasting scheme optimizes channel and computer utilization by forwarding only the tracks required by the HIT-receiving participants. It is not bidirectional and uses low data-rate radio channels, usually on HF for beyond line-of-sight radio-wave propagation.

**TABLE III**  
**Simulation parameters used in the computation of DREV MBMs**

parameter	values/ranges	comments
weapon range	unlimited	Classes of results were stored only for non-organic ranges of engagement, arbitrarily set from 100 to 900 km.
weapon-uncertainty area (WUA) major-axis half-length minor-axis half-length weight function	7.5 km 5.0 km triangular	The same WUA parameters are used for MBMs without a COF.
circular-uncertainty area (CUA) radius probability distribution	5.0 km normal	The same CUA parameters are used for MBMs without a COF.
cost-of-firing (COF)	-0.5	Former MBMs had no COF, which is equivalent to COF = 0.
engagement allegiance factors blue-on-any-orange (POE) blue-on-the-intended-orange (ITO) blue-on-an-unintended-orange (ITO) blue-on-blue (POE & ITO) blue-on-a-neutral (POE & ITO)	1.0 1.0 0.5 -2.0 -2.0	Former MBMs used: (GRV <sup>16</sup> ) 1.0 (SRV <sup>17</sup> ) 1.0 (SRV) 0.5 (GRV & SRV) -1.0 (GRV & SRV) -0.5

<sup>16</sup> This is the general-reward value of the general-engagement measure (GEM), which is an early version of the POE (Ref. 5).

<sup>17</sup> This is the specific-reward value of the specific-engagement measure (SEM), which is an early version of the ITO (Ref. 5).

### 3 PROCESSING OF OUTPUTS FROM SIMULATION RUNS

The results of each simulation run are combined in an output file where each record holds the results of the application of the two models selected in the scenario to a single engagement. A record contains the following information on an engagement:

#### **Engagement profile**

1. engaging ship identification;
2. engaging ship GT location at time of decision;
3. time of decision;
4. intended target identification (as reported in the commander's WAPS);
5. intended target location (as reported or predicted from the commander's WAPS);
6. distance between engaging ship and target location;
7. indicator of intersection between the WUA and the TUA of the actual location of the target (according to the GT);
8. identification of all CUAs intersecting each WUA for every engagement opportunity and scenario.

#### **Engagement outcome assessment**

1. hit probability (indiscriminate for all intersecting CUAs);
2. pertinence reward value (PRV);
3. POE measure of the engagement;
4. target reward value (TRV);
5. ITO measure of the engagement.

Each simulation run produces one such file of raw results; thus the set of simulation runs yielded 48 result files.

Each result file is processed by a classification program that extracts the data from individual records and groups them into files of classes, two for each result file. The first groups the results according to the distance between the engaging ship and the target location (reported or extrapolated); the second according to the value of the POE and ITO measures.

The distance classification file holds eight records, one for each distance class considered. Each record contains the following information on a distance class:

1. distance class range (from 100 to 900 km in class widths of 100 km);
2. class count (the number of cases for which the distance fell within that class range in the result file);
3. number of intersections (the number of times the TUA of the actual target location intersected the WUA, for all engagements in that class);
4. class rate of intersection;
5. mean POE measure of all engagements in the class range;
6. mean ITO measure of all engagements in the class range.

The file that classifies engagement-opportunity measures holds six records, one for each class of measure value considered. Each record contains the following information on a class of measure values:

1. class range of values (from -2.5 to 0.5 in class widths of 0.5);
2. class POE count (the number of engagement cases for which the POE measure fell within that class range in the result file);
3. number of POE intersections (the number of times the TUA of the actual target location intersected the WUA for all engagements whose POE measure fell within the class);

4. class POE rate of intersection;
5. mean distance between engaging ship and target location (reported or extrapolated) of all engagements whose POE measure fell within the class range;
6. class ITO count (the number of engagement cases for which the ITO measure fell within the class range in the result file);
7. number of ITO intersections (number of times the TUA of the actual target location intersected the WUA for all engagements whose ITO measure fell within the class);
8. class ITO rate of intersection;
9. mean distance between engaging ship and target location (reported or extrapolated) of all engagements whose ITO measure fell within the class range.

The classification files are regrouped into spreadsheets. One spreadsheet set regroups the distance classification files: each holds the data of the four distance classification files (one for each WAPS) according to one of the three scenarios used and for one particular day of TIMSIM '93 data. A second set regroups the data from the classification files of the engagement opportunity measures. The reader is referred to Ref. 8 for the detailed results contained in these spreadsheets.

Finally, these results (and some supplementary ones) are summarized in six spreadsheets gathering overall results for rates of intersections, POE measures, ITO measures, time delays, positional errors including all cases and positional errors with "outliers" removed ("outliers" are defined in Chapter 4). They are presented in the Appendix C of this document and discussed in Chapter 5.

## 4 SUPPLEMENTARY ANALYSES AND RESULTS

In addition to the analyses performed based on decision models, several standalone programs were applied to the TIMSIM '93 data to examine descriptive statistics about delays and positional errors. The results are gathered into three sets of spreadsheets, which are included in Ref. 8 and from which we have excerpted the data for this Chapter and for Appendix C.

The first set of spreadsheets looks at the distribution of delays in the WAPS reports, i.e., the interval between the time of report and the position time. There is one spreadsheet per day of TIMSIM '93 data, each containing the results for the four WAPS. Allegiances are discriminated and results are grouped into five time classes, from game minute 2300 to game minute 2900 in steps of 120 minutes. Cases are distributed among these classes according to the position time in the WAPS records. The number of cases and the average of the delays for each class is computed.

The second set of spreadsheets gathers information about positional errors in the WAPS databases. There is one spreadsheet for each day of TIMSIM '93 data. For each report in a WAPS, the mean positional error is computed as the distance between the position reported in the WAPS and the position in the GT at position time. These errors are cumulated over all reports in the WAPS and their mean is computed for classes of distances (distance between the WAPS-reported contact position and the center of the corresponding group of blue ships) ranging from 0 to 900 km in steps of 100 km, all according to the reported allegiance of the contact. WAPS reports lacking identifications (class-names) or with unresolved allegiances are dismissed.

Examination of the positional error spreadsheets reveals several cases in which the mean error is totally unreasonable. By investigating the WAPS data source we found that these instances arose because of incorrect class-name identification by the tracker/correlator in the WAPS files. Although there were very few such cases (fewer than 0.5% of the total number), their affect was strong enough to greatly affect the average of the class. Consequently, a third set of spread-

sheets was produced using the same computations but removing data points whose positional error exceeded 30 km at source or sensor time (position time). We call these cases "outliers."

## 4.1 Discussion of Results from the Supplementary Analyses

Three summary spreadsheets, included in Appendix C, were extracted from these three sets of source spreadsheets. They regroup the previous results for each day of TIMSIM '93 data and for each WAPS without considering the granularity among classes of game time and range found in the source spreadsheets. They are discussed in the next subsection.

### 4.1.1 Positional Errors

A visual inspection of the positional error data (including all cases) at position time in the summary Table of Appendix C shows that in several instances the error is excessive; for example, it is 205.18 km for hostile contacts in SAG1 on Day 2 and 144.77 km for neutral contacts in SAG2 on Day 3. These figures are averages, indicating even greater discrepancies for individual reports. Although this situation occurred mostly for hostile and neutral contacts, it affects the overall error measures significantly. Errors of such magnitude are completely unexpected: since we are looking at the positional error at position time, we would expect errors of the order of magnitude of the sensor positional accuracy.

As was the case in the previous section, tracking down the sources of these discrepancies revealed a few individual instances where the error was so high that it biased the average of the whole class. These errors were introduced by incorrect class-name identification from the tracker/correlator. These particular cases can be viewed as aberrations whose removal does not affect the statistical significance of the results, because they are few in number compared to the sample sizes. On the other hand, *not* removing them would lead to false conclusions being drawn from the results. In the analysis of future exercises it would be desirable to iden-

tify such discrepancies<sup>18</sup>, to count them, to report their causes and to remove them from the positional accuracy estimators, since they properly belong to other measures, such as coherency or human error rate (see RIMPAC '94 and '96, the ground-truth assessment).

Filtering out these cases by setting the maximum allowable positional error to 30 km yields the results given in the summary Table in Appendix C: positional errors with outliers removed. More realistic figures are seen at once in the summary results presented in Table IV. In fact, the error values indicate very good sensor accuracy. For each day, the hostile category has a higher positional error than the friendly and neutral categories. This seems reasonable since it is expected that the enemy would be more difficult to track precisely than friendly or neutral units because of evasive maneuvers on their part or the use of countermeasures against sensor operations. Friendly units report their positions with higher accuracy than provided by some sensors, while neutral units are more likely to follow steady courses, thus favoring better precision in estimates of their positions.

The overall figures shown in Table IV do not indicate much difference from day to day or between WAPS views, with the exception of Day 1 where the FOTC, SAG1 and SAG2 have significantly lower errors than on the other days and for the TWCS, which shows a lower error than for the three JMCIS nodes for every day but Day 1.

Removing the outliers reduced the apparent mean positional error at position time from 24 km to 2 km, ten times lower.

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<sup>18</sup> Tracing the source of such errors may help identifying problems with wide-area tracker/correlator algorithms and procedures. Finding a way to identify them in real-time would reduce the amount of misleading information provided to decision makers and consequently might avoid possible blue-on-blue engagements.

TABLE IV

Overall positional errors without the outliers versus (:) the unfiltered data (excerpt from the summary tables of Appendix C)

overall error (km)	TWCS	FOTC	SAG1	SAG2	overall
Day 1	2.76::14.76	1.25::07.49	1.20::05.23	1.44::34.09	1.66::15.39
Day 2	1.36::15.64	1.95::35.21	1.61::38.76	2.31::34.83	1.81::31.11
Day 3	1.82::11.73	2.64::31.07	2.62::32.30	2.95::40.29	2.51::28.85
Day 4	1.76::09.56	2.00::20.12	2.36::21.57	3.14::25.69	2.32::19.24
overall	1.92::12.92	1.96::23.47	1.95::24.47	2.46::33.72	2.07::23.65

#### 4.1.2 Delays

Delays were measured by taking the difference between the report time and the position time in the contact information reports. The summary table for delays given in Appendix C shows some values that are unexpectedly high. This is especially so on Day 1: e.g., averages of 46.63, 47.74 and 54.75 minutes for hostile, friendly and neutral contacts in TWCS and an average of 50.15 minutes for hostile contacts in SAG1. Many operational problems were encountered on Day 1 of TIMSIM '93, so it is reasonable to assume that systems and processes were not properly tuned that day. There is also a possibility of an effect similar to the "outliers" effect on positional errors: in the case of delays, outliers might be reports on stalled tracks: successive reports sent on a contact without updating the position data. Just a few of these cases lasting for hours would greatly affect the average delay measure. Although such instances were identified in the analyses, they have not yet been investigated systematically to determine their number, source or average duration. It is expected that the removal of a few cases with very high delays due to stalled tracks would significantly lower the averaged results.

During RIMPAC '94 and '96, maximum delay values were observed much in excess of those indicated above. For example, Ref. 10 indicates that track reports for opposed-force FOTCs were as much as 90 minutes old for 7% (one side) and 26% (for its opponent) of their hostile tracks, for 2% and 1% of their friendly ones and for 2% and 14% of the other tracks in the blue and orange force FOTC databases, respectively. These large delays were mainly attributable to the lack of appropriate automated support to the surface-picture managers by systems like JMCIS or the GCCS using the FOTC concept. These figures are noted to indicate that one cannot simply remove unreasonable values without tracing their causes. But when these anomalous values are few in number, fewer than 2% of the number of reports, and their effect on the overall statistics is significant, it is advisable to exclude them.

This aspect of the analysis leads naturally to a recommendation for future systems. There is a strong requirement for better aids to track managers in JMCIS- or GCCS-like systems used to support the FOTC functions or shore fusion centers like MCOIN: they and their users must be alerted to high-interest tracks that are overdue for updating. Track symbology must indicate data aging beyond an agreed-upon threshold for this type of contact. Then, if necessary, surveillance assets can be deployed.

As Table V indicates, with the exception of Day 1 the overall delays for TWCS are significantly lower than for the three JMCIS nodes and the FOTC shows delays always lower than those for SAG1 and SAG2. The difference in delays between SAG1 and FOTC and the difference between SAG2 and FOTC are good indicators of the dissemination time from the FOTC to these two JMCIS nodes. These differences are almost identical, delays to SAG 2 being slightly larger than those to SAG 1, and we conclude that for the volume of data transferred the low communication channel capacity to SAG 2 had less effect than the FOTC procedure that imposes a 15-minute wait before forwarding updated pictures to participants.

**TABLE V**  
**Overall delays (excerpt from the summary tables of Appendix C)**

Overall delays (min)	TWCS	FOTC	SAG1	SAG2
Day 1	51.07	18.79	37.67	35.15
Day 2	12.95	19.25	26.82	34.54
Day 3	13.46	18.38	28.94	25.04
Day 4	11.62	21.58	28.74	27.56
overall	22.27	19.50	30.54	30.57

Delays and positional errors should be strongly correlated since, in a dynamic environment, aging of positional data can be expected to induce errors in position as a function of time. This correlation cannot be established here because the previous results on positional errors were all gathered at position time. To establish the correlation with the delays results of Table V we would need to look at the positional errors at report time and at the difference between that error and the positional error at position time; that is, to look simultaneously at the variation in positional errors from position time to report time as the delay increases. We have not yet quantified this correlation, but all the necessary data is at hand and we hope to report on it in future work. The phenomenon is outside the scope of this document and results on such analyses can be found elsewhere, e.g., Refs. 10, 16.

The question of removing cases of extreme values for delays (as well as for positional errors) has both statistical and logical foundations. First, it is not uncommon in data analysis to filter eccentric values or aberrations. If they are due to an incorrect, erroneous or ill-conditioned behavior of the system being studied and one is not specifically investigating that behavior, it makes sense to eliminate the resulting data gathered, as long as the number of such occurrences is not proportionally too large. Second, one objective of our analysis is to assess the impact of system changes on overall picture quality and on mission effectiveness. Such

changes might be related to performance (more and better sensors, increased bandwidth and data transmission rates) or effectiveness (data fusion, integration, dissemination). We want to be able to compare these changes in an otherwise stable environment, one in which unrealistic, exceptional or ill-conditioned behavior of the systems from one setup to another does not compromise the soundness of inferences made. The analysis results will lead to most significant conclusions when we consider systems operating under "normal" conditions. This does not mean that we are restricted to steady-state systems, but that the amount of variability be realistic and representative of usual conditions of operations. Exceptional events due to abnormal or exceptional conditions must be dealt with separately and are part of other types of measures.

## 5 INTERPRETATION OF THE MODEL-BASED MEASURES

The actual values of the POE and ITO measures range from -2.5 to 0.5. These figures do not convey an absolute but rather a relative appreciation of engagement outcomes. Running the same analyses with different values for the COF and the allegiance factors would yield a different range of values.

With the set of values actually used for these parameters, the interpretation of the measures within the range is quite simple. The upper bound of 0.5 indicates an optimal engagement outcome: a sure hit to an hostile ship (POE measure) or to the intended hostile target (ITO measure). The lower bound of -2.5 is the worst outcome possible: a sure hit to a friendly or a neutral ship (we used the same allegiance factor value for these two categories).

Between these two extremes, we propose the following steps for interpreting the intermediate values. We assume that this scale applies to the aggregated measures (overall) found in the summary tables of Appendix C, thus to the average of the measures on a large number of engagement situations (several thousands, Refs. 5, 8). Table VI shows a possible scheme.

### 5.1 Characterizations of the POE and ITO Persona

The characterization of the POE and ITO measures presented above is a first attempt to provide a simple and meaningful interpretation of the model measures in terms of mission effectiveness or engagement decision productivity. We have applied descriptive labels to equally spaced levels in the numerical range of possible values for the measures in order to give the measures a more natural interpretation. It can be argued whether the number of levels defined over the whole interval (7) is too large or too small. The actual terms used for labels are also moot. However it seems reasonable that the label term used for the lowest numerical value of the measures should indicate a very unfavorable/unproductive engagement outcome and that the label term used for the highest possible value of the measures should mean a very favorable/productive one. Between these two extremes the label terms should indicate an increasingly favorable outcome.

**TABLE VI**  
**Proposed mapping between a MBM computed value and its interpretation,  
 a cardinal or label**

value range	description and label
0.5	most productive situation, enemy ships are always hit, this level will be labeled "best" hereafter
]0.0, 0.5]	highly productive
0.0	productive situation; a typical case yielding this ITO value would be to hit a hostile ship other than the intended one. "Good" will be used as a label for this level of success
] -0.5, 0.0]	marginally productive
-0.5	"marginal" level; anything below this point is counterproductive. A typical case is when there is no contact whose CUA intersects the WUA and the weapon is fired uselessly
] -1.0, -0.5]	marginally counterproductive
-1.0	counterproductive cases outweigh productive ones: e.g., only three ships out of four intercepted are orange; label "counterproductive" due to the COF
] -1.5, -1.0]	very counterproductive
-1.5	"extremely counterproductive," e.g., only two orange ships out of three ships intercepted
] -2.0, -1.5]	exceedingly counterproductive
-2.0	undesirable situation in which the blue force destroys as much of its own or neutral ships as it destroys the orange; label "quasi fratricide"
] -2.5, -2.0]	fratricide
-2.5	most undesirable situation in which blue force destroys only neutral/friendly ships rather than hostile ones; this level is labeled "worst" or "total fratricide"

Using equally spaced levels within the interval range more or less assumes a degree of linearity in the increase of the "goodness" of the outcome. This may not necessarily be the case. For example, it is possible that a small increase in the numerical values at the high end of the scale results in a more significant increase

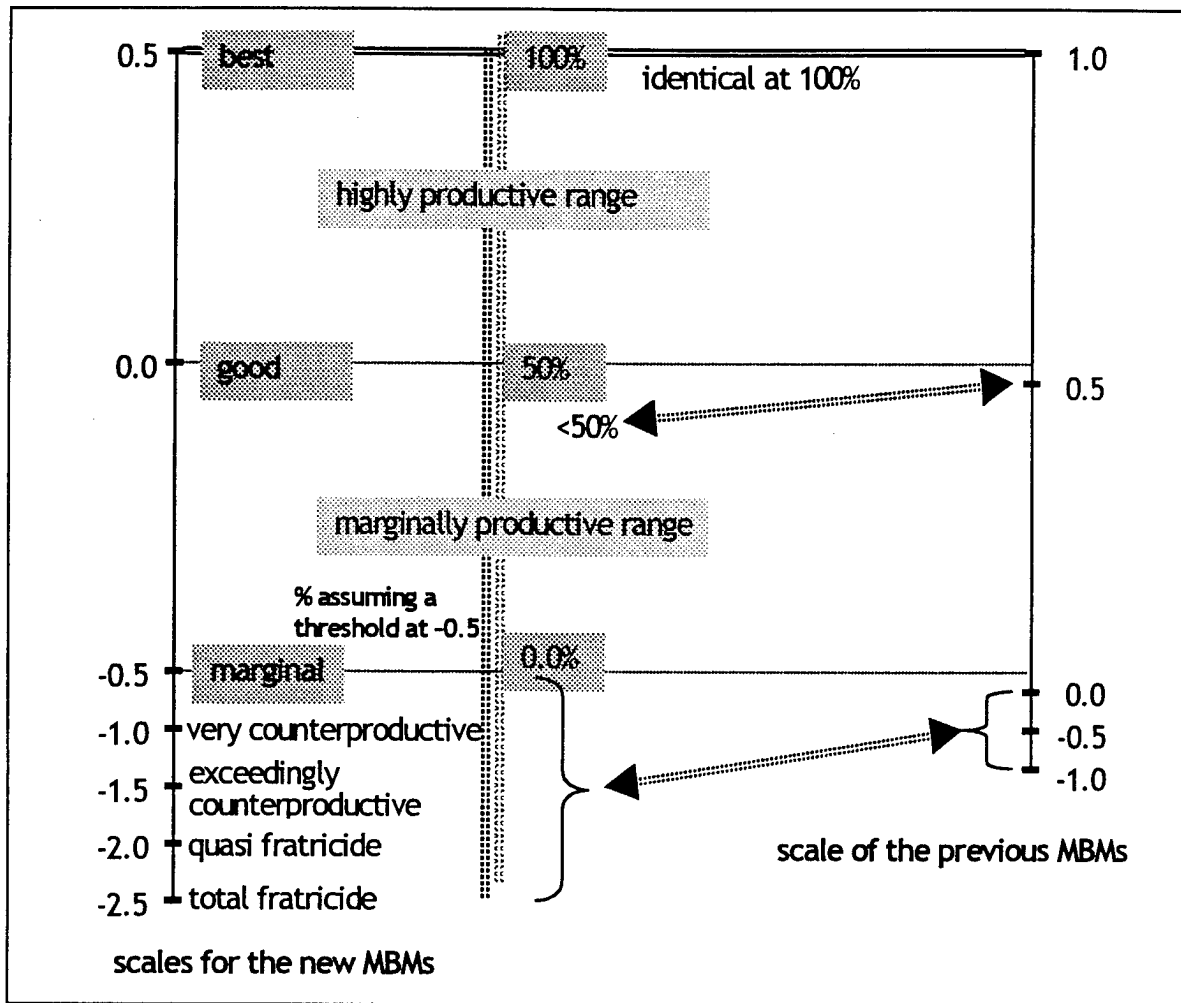
of productivity or effectiveness than the same increase in the middle or lower part of the scale.

Adjustments can be made by selecting unequal subinterval lengths between adjacent levels or by using a sequence of label terms whose connotation does not vary linearly from one label term to the next. The latter means is very questionable, since it relies highly on the subjective interpretation of the label terms and it would be very difficult to choose a set of terms that would consistently represent an appropriate increase in productivity from one step to the next. The former means appears more practicable; i.e., use unequal subinterval lengths between adjacent levels. We propose to use a very simple set of label terms, one containing from four to eight very basic terms possibly qualified by intensification adjectives. They should be chosen so that when they are ordered, they convey a more or less constant increase in the intensity of their connotation. For example, "worst," "bad," "insignificant," "good," "best." These would then be applied to unequally spaced levels over the whole interval of values according to the actual correspondence or distribution of the measure.

The problem of selecting the lengths of the subintervals or, equivalently, the unequally spaced level points is the most difficult part. In the absence of cumulated results from an insightful set of exercises, one may apply a mapping based on a threshold, with all values above the threshold mapped to a value from 0.0% to 100%. At the threshold the value is 0%. Values below the threshold are negative percentages, following the scaling imposed by the positive values. Furthermore, since we are interested in productive systems that are capable of improving mission success rates, the focus must be on the positive segment of this mapping, i.e., from 0% to 100%, which might correspond to cardinal values marginal to best.

### 5.1.1 Mapping between MBM Scales

A tentative mapping between these representations and the scales for the present MBMs and their former versions is illustrated in Fig. 7. We assume that the scales are imposed by the new and old DREV MBM definitions and by the parameters specified above. By setting the threshold at -0.5 for the new MBMs we can force their percentage values to approach closely those of the previous MBM ver-



sion. This mapping is valid only when the rate of successful engagements is much larger than that of failures. It also requires the assumption of the parameters indicated previously for the COF, CUA, WUA and rewarding values per allegiance: the current version with a COF of -0.5 and a maximum penalty of -2; the previous version with no COF and a maximum penalty of -1.

The raw results from the POE and the ITO that include any significant COF are much lower in value than those obtained with the measures defined for the previous MBMs (which do not include a COF component). However, the new measures deliver relative results that are almost identical to those given by the early

version of the MBMs. The new version (including COF and other resource contingencies) described in this document offers the advantage of being closer to a realistic scale, although empirical calibration is still required, particularly to provide specific COF values for each combination of weapon and target, based on tactical and economic impact.

### 5.1.2 Statistical Characterization

As experience is gained with the models by applying them to larger sets of controlled experiments, a statistical basis of inference for the behavior of the overall measures should emerge, independent of the COF and allegiance factors. This would allow a more refined stratification of assessment where the intervals of values for the overall measures are not necessarily the same for each mission effectiveness assessment label, e.g., extremely effective or productive, very effective, effective, poor, and so on. The statistics should be separate for each scenario (delay, no delay, delay with prediction), for each measure (POE and ITO) and for each WAPS (TWCS, FOTC and others), since samples should be drawn from homogeneous populations. Though the range of possible values for a given statistic may change according to values set for the COF and the allegiance factors, the general shape of the distribution is likely to be the same over several experimental samples.

For example,  $P_{Tnd}$  (the probability variable POE for the TWCS with no delay) may be defined as a stochastic variable representing overall POE measures sampled on a set of experiments (or subsets of engagements from a set of experiments) using "no delay" scenarios and TWCS information systems. Statistical variables defined under these conditions (the same type of information system and the same type of scenario) should exhibit the typical distribution. That distribution may not be the same for variables defined over different information systems and different scenarios or it may be a similar function but with different characteristic parameters, e.g., mean and variance. Possibly the "no delay" and "delay without prediction" populations (for the same type of information system) could be merged into a single population of experiments since the "no delay" scenario duplicates the lower extreme values of the "delay without prediction" scenario.

In order to find the distributions of typical measures that are characterized by a set of conditions (e.g., the same type of information system and scenario), exploratory empirical distributions are generated by selecting susceptible sets of conditions for which we expect to observe differences. In such cases the experience of the analysts must determine the course of action to be taken, otherwise one may focus on non-significant variations of the data for a particular study.

## 5.2 Results

### 5.2.1 Intersection Rates

In each series of results from the application of the six models described in Chapter 2 the "intersection rates" of CUAs with WUAs is a primary result that is used in MBM computation. Intersection rates without delay, with delay and no prediction, and with delay and prediction have a strong correlation with their corresponding MBMs. These intersection rates express the scenario prerequisite conditions for an engagement situation for the six MBMs.

Table VII lists the overall intersection rates (see Appendix C). A comparative bar chart illustrates these values in Fig. 8. The intersection rates represent the proportion of engagement situations where the CUA of the hostile target intersected the WUA at the time of decision. These are important indicators directly related to the effectiveness of an engagement decision. Indeed, notwithstanding the possibility of other contact CUAs intersecting the WUA, a higher intersection rate favors a successful engagement outcome. The chart shows a consistent degradation of intersection rates from the ideal model involving no delay, through delay applied without prediction, to delay with dead-reckoning. Unsurprisingly, all the WANTAP systems considered are affected by this degradation due to information aging, so it is reasonable to assume this behavior to be independent of the particular information system considered (but *not* independent of its timeliness). Using a different predictive scheme might improve the intersection rates for the delay-with-prediction class if such a scheme were to mimic more closely the expected maneuvering of hostile ships after their detection. The scenarios and intersections are explained with the definitions and related illustrations (Figs. 1-6) presented previously.

**TABLE VII**  
**Intersection rates (%)**

model	TWCS	FOTC	SAG1	SAG2
no delay	91.1	84.6	84.2	81.1
delay (no prediction)	62.3	58	45.7	46.3
delay (with DR prediction)	47.5	45.1	33.8	36.5

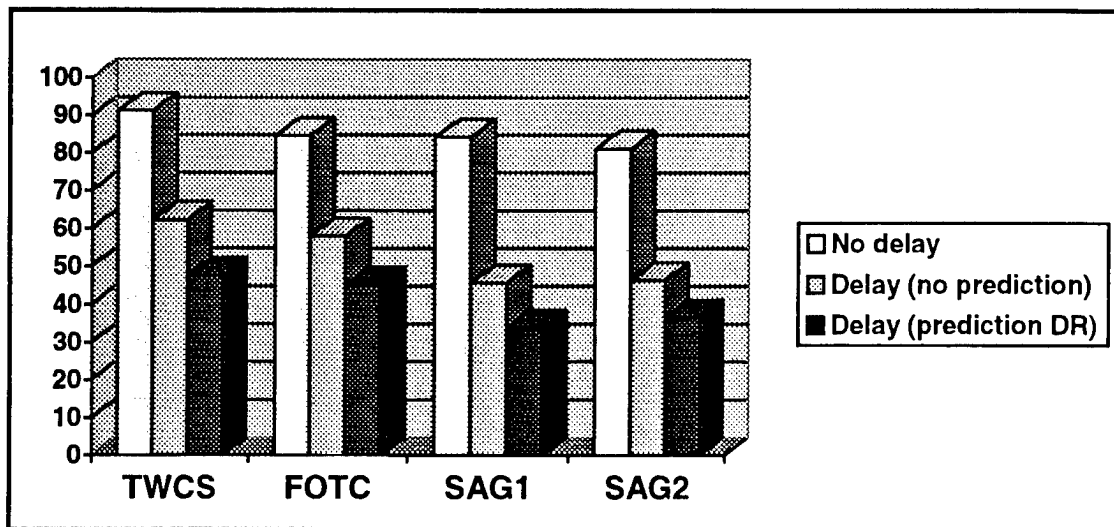


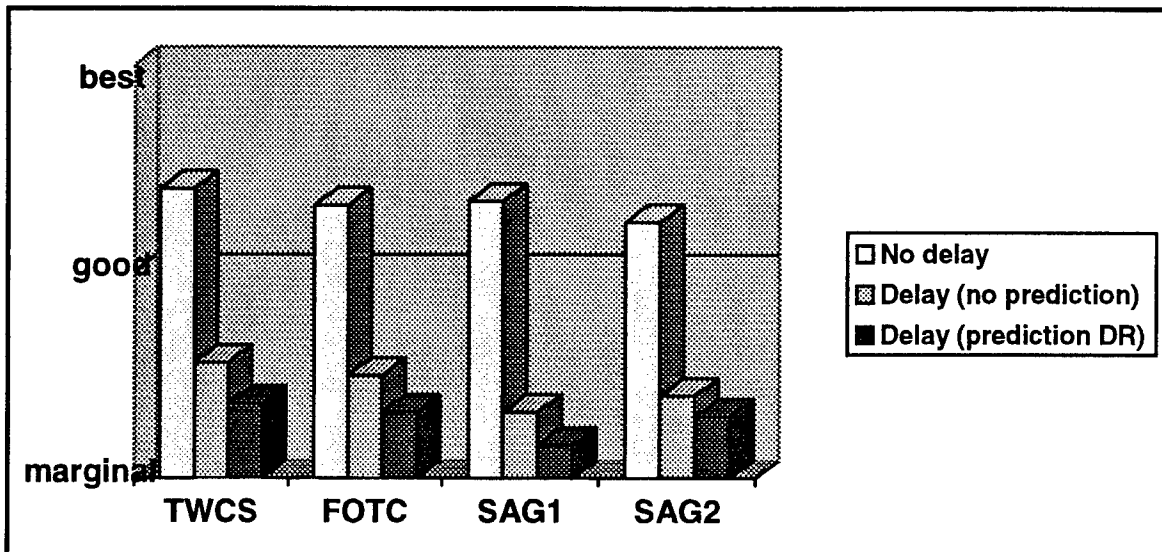
FIGURE 8 - Chart of intersection rates

The intersection rates for the data without delay from the sensors indicate the ability of the sensor suite feeding a WAPS to estimate the position and allegiance of contacts accurately. We use this for our sensor baseline. Nominally, from the point of view of improving the reported tracks scrutinized by this measure, the maximum achievable theoretical improvement at the TWCS is 9%<sup>19</sup>. This limit disregards the limitations due to physics or to scenario constraints, so for the hostile-ship picture the maximum feasible sensor improvement must be much less than

<sup>19</sup> We found 8% in a previous analysis of the raw data from the same experiment (Refs. 5, 12).

**TABLE VIII**  
**Overall POE measure**

model	TWCS	FOTC	SAG1	SAG2
no delay	0.2 (70%)	0.16 (66%)	0.17 (67%)	0.12 (62%)
delay (no prediction)	-0.22 (28%)	-0.25 (25%)	-0.34 (16%)	-0.3 (20%)
delay (with DR prediction)	-0.32 (18%)	-0.34 (16%)	-0.42 (8%)	-0.35 (15%)



**FIGURE 9 - POE engagement action productivity (pertinence)**

9%. Since our measure, this intersection rate, is invariant to completeness, it is not affected by sensor deployment but by the ability of the sensors to provide correct allegiance and position.

### 5.2.2 Pertinence-of-engagement Measure Results

Table VIII lists the overall POE measure results (see Appendix C). These results are converted and charted in Fig. 9 by applying the previous interpretative

labels to the actual numerical values. The same typical behavior appears, i.e., a degradation in productivity (mission effectiveness) as delay is introduced in the model; more so if dead-reckoning prediction is used. Though the scales used are not the same for the POE measure and the intersection rate, there is even more discrepancy here between the delay and no-delay models. The intersection rate does not account for the distance between a contact whose CUA intersects the WUA and the center of the WUA. The POE measure accounts for that distance by assigning a lower probability of being hit as the distance increases. Since the introduction of delays in the data increases positional errors, a greater discrepancy is expected for the POE measure. In addition, the intersection rate is not sensitive to the presence of other contacts whose CUA might intersect the WUA, but the POE measure is very responsive to the presence of other contact CUAs in the vicinity of the WUA and to differences in allegiance: a possible friendly and/or neutral ship in the WUA greatly decreases the POE measure.

### **5.2.3 Intended-target-opportunity Measure Results**

Table IX lists the overall ITO measure results (see Appendix C). The results are converted and presented with the proposed labels in the chart of Fig. 10 in the same manner as for the POE measure. As one would expect, the degradation pattern is similar to that observed for the POE measure. The difference lies in slightly smaller values for all groups and models. This small difference is caused by the lower allegiance factors attributed to hostile ships other than the intended target in computing the ITO measure. However, the same discrimination among ship allegiances in the vicinity of the WUA applies here, further emphasizing the gain in productivity when there is no delay.

**TABLE IX**  
**Overall ITO measure**

model	TWCS	FOTC	SAG1	SAG2
no delay	0.17 (67%)	0.12 (62%)	0.13 (63%)	0.08 (58%)
delay (no prediction)	-0.23 (27%)	-0.27 (23%)	-0.36 (14%)	-0.31 (19%)
delay (with DR prediction)	-0.33 (17%)	-0.35 (15%)	-0.43 (7%)	-0.37 (13%)

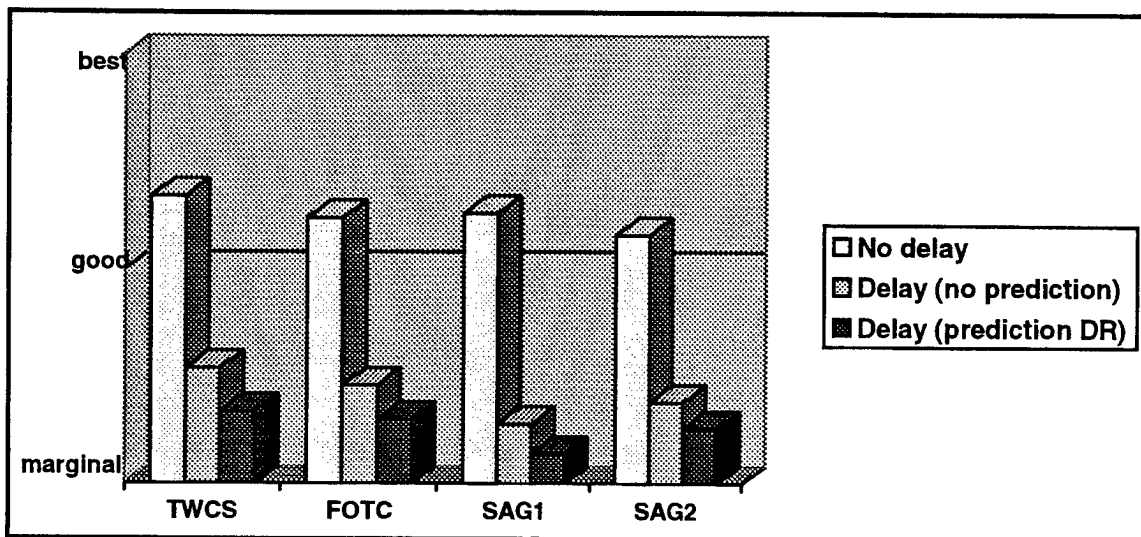


FIGURE 10 - ITO engagement action productivity (intention)

### 5.3 Quantitative Comparison between the MBM Versions

Table X lists the overall ITO measure results compared to the SEM (its previous version), in percentages. The differences ( $\Delta = \text{SEM} - \text{ITO}$ ) are presented in Fig. 11.

**TABLE X**  
**Overall ITO measure versus the SEM measure**

model / ITO::SEM in %	TWCS		FOTC		SAG1		SAG2	
no delay	67	65	62	60	63	64	58	61
delay (no prediction)	27	30	23	27	14	19	19	24
delay (with DR prediction)	17	19	15	18	7	11	13	18

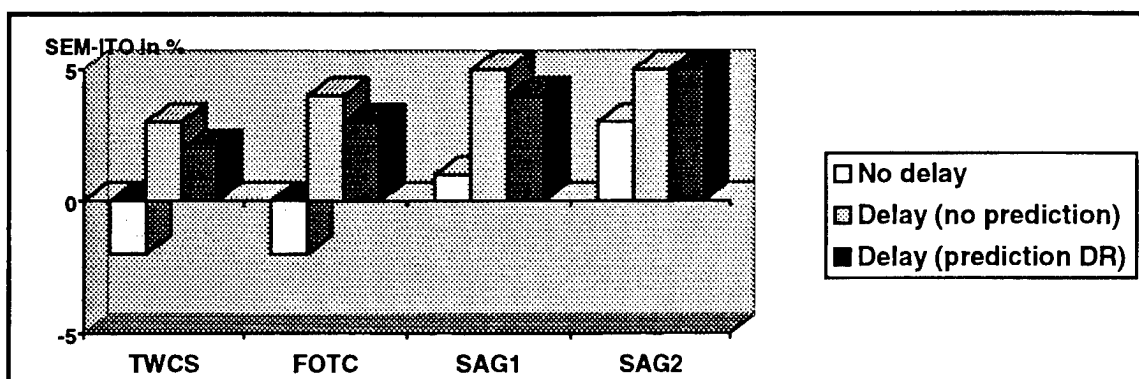


FIGURE 11 - Difference between the % of the SEM and the ITO measures

As one would expect, both measures offer similar figures of merit, although the new version of MBMs tends to deliver lower numerical values for most of the cases except<sup>20</sup> those at no delay for the TWCS and the FOTC. The slightly smaller values of the ITO (maximum of -5%) can be accounted for by the larger allegiance-factor penalties assigned in the ITO measure, as compared to the SEM measure (see Table III: the SRVs are -0.5 and -1.0, versus -2.0 for the ITO). Nevertheless, the metric was preserved and conclusions drawn from the data with the previous version of the MBMs are essentially the same.

<sup>20</sup> We suspect that the removal of a few outlier cases in the new input data sets used for the POE and ITO tests may explain this discrepancy, especially when we approach higher mission success rates.

## 5.4 A Measure of Completeness

For a given geographical area and period of time and a specific WAPS, a fair measure of completeness is how many and how often GT tracks have been located and identified correctly. To establish this for a common operating picture (COP) shared among decision makers we have to assess all replicates of the tentatively shared database (each located in a given WAPS of a battle force), then count only the correctly reported contacts that are common to all the replicates. The common part is the completeness of the shared COP. The union or perfect combination of the results across all the replicates (the best WAPS picture) is the completeness of the achievable COP, given no loss in information management and exchange. Differences in completeness indicate the lack of coherency among the replicates.

Completeness for one WAPS assumes the following: there are several databases to be sampled and a GT file is reconstructed from a coherent combination of all available sources (GPS-recorded position reports, all the information databases including opponent databases in military exercises and the stimulating files used in simulations). For all surface contacts in the geographical area and the time period specified for the analysis, the GT is sampled at discrete times (sampling every 15 minutes is sufficient and practical in most scenarios)<sup>21</sup>. Each GT point contains the time, the identification of the contact and its allegiance. The completeness measure algorithm is then as follows:

1. Find the corresponding contact within a given CUA for each GT point in the WAPS database under test.
2. Count one (1) for a correctly reported contact at that time. If subsequent GT points of the same track refer to the same WAPS report and it is still within the CUA with the correct identification continue to count additional ones ( $n + 1$ ). If no correct reports corresponding to the GT point are found, count nothing (0).

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<sup>21</sup> Instead of using the elapsed time to sample the GT file, one can use a thresholding technique (draw a new sample when changes are beyond a threshold for a given track parameter), Ref. 3. An evaluation of completeness based on a threshold technique is expected to be more accurate and fair than one based on delays only. It is a kind of model-based measure for completeness and it can be extended to support the optimization of surveillance-asset deployment.

3. Cumulate the number of GT points used and the total occurrence of correctly reported contacts in the WAPS database.
4. Compute the ratio of the occurrence of correct reports to the total number of GT points and report it as the measure of completeness of the WAPS database for that period and geographical area.

This measure of completeness of a tactical picture assesses several aspects of the systems, scenarios, decisions taken, resource management, sensor performance and of surveillance-asset deployment. It is significantly different from the intersection rates reported for the MBMs. For the latter rates we count the number of times each track update of a WAPS intersects the GT, then analyze only the tracks in the commander's database. For the completeness measure we count the number of times each track update of the GT sampled every 15 minutes intersects the correct WAPS track report.

The lack of correct track reports on some contacts in the best WAPS picture depends strongly on surveillance-asset deployment and sensor performance. At sensor time, a lack of correlation between WAPS track reports and GT reports cannot depend strongly on the deployment of surveillance assets but rather on sensor performance<sup>22</sup>. At report time at the compilation node, it depends mainly on information management. At remote nodes, it depends on both information management and communications. Consequently, MBMs and intersection rates do not depend strongly on surveillance-asset deployment, while the proposed measure of completeness does. This is illustrated and supported by the following results excerpted from previous analyses on the same exercise data (Table XI and Fig. 12).

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<sup>22</sup> The data transfer rate from the sensor to the compilation node is assumed to have little effect compared to other processes, as observed during certain exercises, Refs. 3, 9, 10.

**TABLE XI**  
**GT versus WAPS intersection rates**

overall rates	TWCS	FOTC	SAG1	SAG2
GT, for all tracks (20 nmi)	0.264	0.343	0.348	0.148
WAPS, for hostile only	0.911	0.846	0.842	0.811

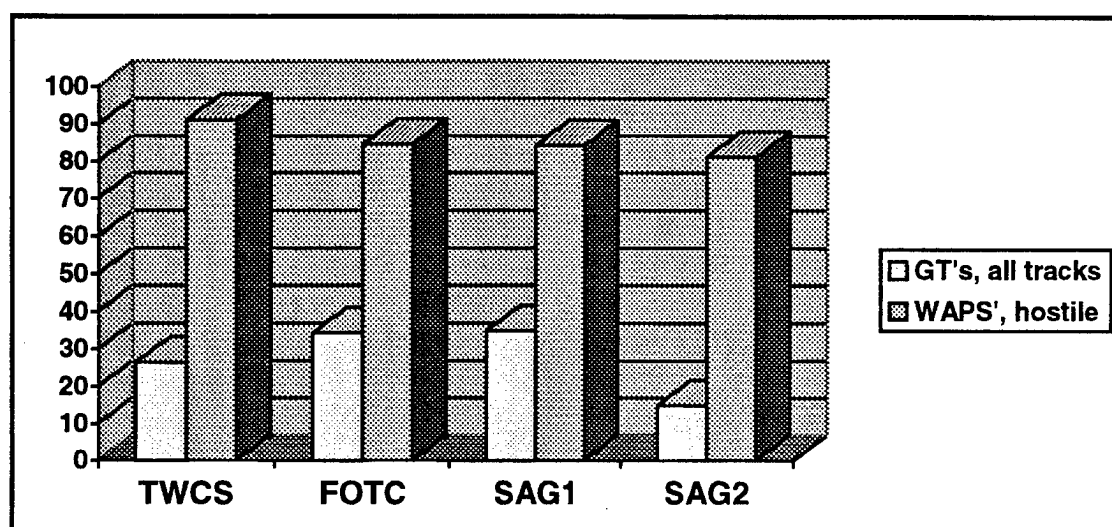


FIGURE 12 - GT and WAPS intersection rates for all tracks (any allegiance) and hostile tracks, respectively

It is worth noting that the WAPS surface hostile picture is best for the TWCS, as it should be for an over-the-horizon weapon-control station. Unfortunately, due to procedures, data management (a man-intensive activity) and other time-consuming activities, the quality of the picture is marginal by the time the data is made available to decision makers, as shown in Figs 8-10. Other information sources and mechanisms are used to refine the OTH-T.

Figure 12 shows that in assessing system performance and mission effectiveness one may need to dissociate the effect of surveillance-asset exploitation (GTs) from the effect of exploiting the available information (WAPS).

From the information of this section, we conclude that if one wants to assess MOPs or MOEs independently of surveillance-asset deployment then measures must be modified to be similar to the MBMs, for example by selecting only the concerned WAPS data and using the GT to assess their quality, rather than starting from the GT data and searching for counterparts in the WAPS data, or by increasing the measure sensitivity by rejecting data that interferes with the phenomenon under investigation. The technique is equivalent to using appropriate band-pass filtering and processing to get a signal out of noise.

## 5.5 A First-order Approximation of the POE or the ITO Measures

Extracting the current POE or the ITO measures is compute-intensive, requiring the computation of the bivariate joint probabilities resulting from the intersection of the CUAs and WUA. These probabilities can be computed by using either brute-force Monte Carlo or numerical-integration techniques. For each intersection we use a thousand point semi-Monte-Carlo technique, described in Ref. 5. This is the compute-intensive aspect of the DREV MBMs. For data files too large for the fast memory of the computer, which therefore require multiple accesses to disk, the proposed approximation may not provide as great a performance improvement as is indicated below, but the speedup will still be impressive.

The first-order approximation algorithm is as follows:

1. Find the GT track sample at decision time (position time and report time, or a later time for decision making) that is the closest to the track report update that triggered the measure. Then compute the apparent miss-distance<sup>23</sup> or targeting positional error.

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<sup>23</sup> This is the pointing error and not the expected miss distance, which requires a knowledge of the detailed engagement scenario, the missile characteristics and the signatures of the target and surrounding disturbances.

2. Associate<sup>24</sup> a hit probability as a function of the miss distance found and multiply the result by the allegiance factor (POE or ITO).
3. Cumulate the results as in the standard POE and ITO measure computation; that is, for a given class of scenario and database conditions, e.g., a given time period, geographical area and WAPS node.

The first-order approximation is a counting process that does not account for multiple CUAs intersecting the WUA. It is expected that the processes would deliver similar results over sample sizes in excess of 100, with as little as 1/1000 as many computing operations, a smaller memory requirement and shorter code. A second-order approximation can easily be designed for in-the-field quasi-real-time post-exercise analyses. A possible modification to the first order may include replacing in Step 2 the probability computation for a single CUA by one for multiple CUAs intersecting the WUA based on the multiple miss distances found and by multiplying the result by the allegiance factor of the winning target (this requires the generation of a random outcome based on the probabilities found).

## 5.6 Looking-glasses

Measures can be compared to looking-glasses: they provide a view of the universe that is limited in the same way as is the image that a specific mirror can produce. If one delivers an image that has a large field of view, objects look smaller and farther away than they really are (as in a car's right rear-view mirror in North America). Small objects are not noticeable at all, although the observer may know that they are there. The opposite situation is the looking-glass that magnifies objects but presents a smaller field of view. It is convenient when we want to focus on specific objects that are either small or far away. Even the perfectly flat mirror, which does not distort the image, still has a limited field of view.

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<sup>24</sup> It can be inversely proportional to the miss-distance with a threshold at the sum of the CUA radius and the WUA radial value at this angle or its mean radius. It is zero at the threshold and beyond it.

In the measures presented above we can consider the intersection rates as a flat mirror, the POE as a magnifying glass and the ITO as one with a certain ability to magnify the usefulness of information to decision making, and thus to increase mission effectiveness. This is demonstrated by the following estimates based on these measures.

Assuming that information management (IM) has similar effects at each node, we can deduce several things about system performance from Table VII. Because of the architecture used during the military exercise studied, at the TWCS and FOTC nodes the normalized decreases  $((\text{FOTC} - \text{FOTC with delay}) / \text{FOTC})$  in intersection rates are an indication of the time degradation resulting from information management, development of the hostile surface picture and all the processing from sensors to the WAPS database, at report time. We will apply the same rationale to the POE and ITO results.

Assuming that the track reports for contacts beyond SAG1 and SAG2 sensor ranges found in these databases rely on communications from the FOTC, the effect of communications on mission effectiveness can be estimated by the normalized difference  $((\text{FOTC delay} - \text{SAG delay}) / \text{SAG no delay})$  of the results between the FOTC and a SAG. The estimate based on the intersection rates does not correspond exactly to the same set of data since it includes all intersections, whereas the POE and ITO results are limited to the sets for OTH-T for ranges from a SAG from 100 km to 900 km.

TABLE XII

## Cost in information management and information exchange

normalized in %	IM cost at the TWCS	IM cost at the FOTC	exchange to SAG1	exchange to SAG2
intersection	31.6	31.4	14.6	14.4
POE	60	62.1	13.4	8.1
ITO	59.7	62.9	14.3	6.9

Previously, we determined that the sensor data were fairly accurate, accounting for 9% of intersection misses. In Table XII we find evidence that IM at the TWCS and FOTC nodes is more costly in terms of OTH-T mission effectiveness<sup>25</sup> than in terms of the positional accuracy of the reports (intersection rates): about 61.2% versus 31.5%, respectively. In estimating the effects of communications on the rates, the POE and the ITO at SAG1 indicate no distinctions between these measures but a small distortion for SAG2. A possible explanation for this is the fact that less data were transferred to SAG2 compared to SAG1, due to the HIT broadcast originating at the FOTC. Consequently, a smaller segment of the data at SAG2 depends on the data received from the FOTC; SAG2 relies more on Link or local data than SAG1.

For the experimental data studied in terms of the hostile ship picture we obtain conclusions that are consistent with those reported in Ref. 12 for an earlier version of the MBMs. They are summarized in the next chapter.

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<sup>25</sup> With the SEM of the MBMs we reported 55% instead of 62%. This is due to the differences explained earlier about the larger penalties for hitting the wrong ship. Consequently, the new MBMs have more magnifying power in terms of the OTH-T mission effectiveness than the previous ones.

### 5.6.1 Impact of Data Aging

Using the same strategy for assessing the impact of data aging on the ITO measure or OTH-T mission success rate, we find a relative loss of 66.5% over 25.7 minutes if we combine the results for all the nodes (TWCS, FOTC and two SAGs). For the SEM it is 60%. These are equivalent to a loss of information value of 12.9% per five minutes, if we assume that it decreases linearly from the initial time each report is generated. For the SEM it is 11.6% per five minutes for all the nodes. At the FOTC we observe a shorter mean delay of 19.5 minutes and conclude for ITO 62.9% and SEM 55% degradations that the impacts of information aging are 16% and 14% per 5 minutes, respectively. The difference between these results and the previously reported values is primarily due to the assumption of a 25-minute mean delay, rather than the 20-minute delay reported here.

We do not expect the rate of the impact of data aging to be linear ( $\Delta \text{impact} / \Delta \text{age}$  is not linear). It is likely to follow a Rayleigh density function, with the value of the delay resulting in the maximum data-aging impact rate depending on the parameters of a MBM. We intend to investigate this aspect with the same data and models but by sorting the results as a function of the report delay for two sets of MBM parameters. Goodness-of-fit tests can be used to assess the soundness of our hypotheses. We expect the maximum rate of data-aging-impact to occur at a delay close to 9 minutes for the current parameters. One may consider this value to be the critical information age for a decision, task or mission for a given success rate.

## 5.7 Causality

Although links between MOPs and MOEs are implied by the ITO and POE MBM definitions given in Chapter 2, little has been said about the specific MOPs that are sensed by the six MBM models used. A tentative identification follows of the sensitivity of MBM models to certain MOPs: their ability to link a particular MOP to the OTH-T effectiveness of a warship.

### **5.7.1 Relevant MOPs**

International organizations are attempting to define standard sets of MOPs to assess command and control information systems and to allow fair comparisons of test results, but there is still no recognized standard definition and "code-of-practice." The MOPs summarized in Table XIII are, in the opinion of one of the authors, those needed to demonstrate the value of MBMs.

### **5.7.2 Examples of Causality Dependence of MBMs**

In Table XIV we show that a combination (relative or differential) of Models 1 and 2 at the FOTC is a good causal indicator of the impact of information currency, management delay and timeliness for OTH-T. The combination of Models 1 and 4 is an indicator of identification correctness. Model 4 at the FOTC, relative to Model 4 at a SAG, is a good causal indicator of information coherency, but with particular emphasis on the information exchange loss between the FOTC and the SAG, while the Model 5 combinations for these databases give indications of information coherency, currency and timeliness but with emphasis on information-exchange delay.

Such mapping of MBM dependence and indications of the impact of MOPs on the mission success rates needs further investigation and will be the subject of further research.

**TABLE XIII**  
**Selected measures of performance**

<b>MOP</b>	<b>description</b>
<b>allegiance correctness</b>	The probability that the allegiance assigned to the contact is correct. This is a condition for identification correctness.
<b>identification correctness</b>	The probability that the unique identification of the contact is correct.
<b>information coherency</b>	Information or picture coherency among participating units indicates the percentage of data shared simultaneously within a given time window and geographical area, for a particular type of data required for a task.
<b>information completeness</b>	Information or picture completeness at each database is the percentage of data that is correct and timely, relative to the available data from all sources (ideally the ground truth). It may be defined for a particular task.
<b>information conciseness</b>	Information or picture conciseness is the quantity of data in a database that is "free from all elaboration and superfluous detail" divided by the total number of data items. The maximum value is one.
<b>information currency</b>	Information currency is inversely proportional to data aging. The age of the data is the elapsed time since last report before consideration (sampling time). It may include time delays from any of the processing stages. Once related to a required decision or task time for a given success rate it becomes the timeliness of that information for an opportunity.
<b>information exchange delay</b>	The time required for exchanging information from one database to another. It impacts the inter-database coherency and currency.
<b>information exchange loss</b>	The amount of information loss from one database to another. It impacts the inter-database coherency.
<b>information management delay</b>	The time required to process a contact report from the time it is generated by the source or sensor to the time it enters the local database and becomes accessible for decision making.
<b>position accuracy</b>	The relative or geographical precision of the position of a contact (may include estimations of speed, altitude and attitude). It is usually expressed in terms of areas or values of uncertainty.
<b>timeliness</b>	Timeliness is how timely a piece of information is for a task or decision. To be distinguished from information currency.

TABLE XIV

Mapping of MOPs on the MBMs assuming three levels of dependence: "d" for strong dependence, "i" for strong independence and "w" for weak dependence ("a" for the FOTC and "b" for a SAG).

causality	MBM model number or combination of numbers									
	POE			ITO			combination			
MOP	1	2a	2b	4	5a	5b	1a:2a	1:4	4a:4b	5a:5b
allegiance correctness	d	d	d	d	d	d	i	i	i	i
identification correctness	i	i	i	d	d	d	i	d	i	i
information coherency	i	i	i	i	i	i	i	i	d	d
information completeness	i	i	i	i	i	i	i	i	w	w
information conciseness	i	i	i	i	i	i	i	i	i	i
information currency	d	d	d	d	d	d	d	i	i	d
information exchange delay	i	i	d	i	i	d	i	i	i	d
information exchange loss	i	i	i	i	i	i	i	i	d	w
information management delay	i	d	d	i	d	d	d	i	i	i
position accuracy	d	d	d	d	d	d	w	i	i	w
timeliness	d	d	d	d	d	d	d	i	i	d

Table XIV is a tentative mapping of MOPs on MBMs and some of their combinations.

## 6 CONCLUSIONS AND RECOMMENDATIONS

An analysis of the results obtained with the new DREV MBMs for a simulated military exercise follows, including a comparison with the results obtained using the earlier version of the MBMs. Only the significant results that offer insight into synthesis or systems issues are presented.

Despite the complexity of the systems evaluated, the new measures were able to recognize changes and variations in the systems and in the opposing forces that the current or classic MONIME measures did not detect or identify.

*The reported method and its improved version thus offer better discrimination among system options and reduce development risk by accurately estimating the impact that changes in procedures, systems and information have on mission effectiveness.*

Results from the new version of DREV MBMs (previous version results are between parentheses) lead to the following conclusions:

1. Improvements in WANTAP capabilities versus hostile ships that can be obtained by optimizing sensor suites appear to be limited to about 9% (was 8%), and that gain is possible only if the WANTAP systems themselves are optimized first;
2. changes in WANTAP systems and procedures can improve performance in excess of 63% for the ITO (was 55% for the SEM), from the reference value at sensor time at the FOTC node (assuming instantaneous track management and information exchange);
3. improvements exceed 77% (was 70%) at the Surface Action Group 1 (SAG1) nodes under the same conditions, providing that communications improvements from the FOTC to the SAGs are made (i.e., including the assumptions from 2); and finally,
4. communications impact the distributed picture by only 14% all cases at SAG1 (was 15% for SAG1 intersection rate), about 1.5 times as much as sensors.

The most important step to improve overall performance is better exploitation of existing sensor and source data by improving WANTAP systems, concepts and procedures at the tactical information management node or in a distributed version of it.

Based on the results obtained for hostile surface contacts and for the surveillance deployment used during the exercise, an improvement of 4% in sensor performance alone, without improving the WANTAP systems and communications, would provide less than 1.3% (was 1.6%) improvement to the shared picture. This apparent loss in exploiting available information may be of concern to users and to experts such as the members of the Copernicus Requirements Working Group (CRWG), who are developing improved JMCIS or GCCS and related architectures and procedures.

Another important result from the data examined using the proposed decision-based measures of goodness is a simple rule of thumb that the hostile-surface WANTAP usefulness degrades by 12.9% (was 11.6%) per 5 minutes of data aging for the four databases observed, with an average delay of 25.7 minutes. At the FOTC the observed shorter mean delay of 19.5 minutes with 62.9% ITO and 55% SEM degradations implies that the impacts of information aging here are 16% and 14% per 5 minutes, respectively.

Better transfer of sensor, intelligence and Link 11 data is required to improve the assistance that WAPS provides for commander decisions. We recommend that operators and commanders afloat be provided with more efficient data management aids, including some automation in the selection, exploitation, fusion and integration of Link 11 data.

Investigations of the effectiveness of dead reckoning show that using this estimator can *decrease* the value of the displayed hostile picture by as much as 67%. Consequently, we strongly recommend that its use be avoided, except to display merchant-ship information.

Using these MBMs significantly reduced the dependency of measured values—the results of the study—on the actual detailed decisions—how surveillance

assets were deployed, for example—made during the exercise. By simulating decisions applied to each valid scenario, the proposed measures of goodness were also shown to be independent of the style or training of decision makers.

This report demonstrates the feasibility of statistically estimating the impact of information and systems quality on decision outcomes and mission effectiveness. Generally speaking, raw data that directly relates the quality of command information systems to measures of effectiveness are sparse and expensive to obtain, so it is very difficult to demonstrate information and systems qualities and their impacts on decision outcomes and mission effectiveness. DREV model-based measures address this difficult problem. They improve estimation accuracy using the same raw data currently available from instrumented military exercises. Both versions of MBMs provided insights that were not available with the measures currently applied to such data. This can be confirmed by comparing our results with those in Refs. 9-11, 14-21.

For the hostile-ship picture found in a commander's database, we have defined two model-based measures to capture the essential components of the impact of the information used in engagement decisions: the POE for the pertinence of engagements and the ITO for the intended target opportunity. The ITO measure amplifies the POE's significance by assigning a smaller reward if the hostile target that is intercepted is not the intended one. Both measures use a fixed cost for launching a missile and both compute interception probabilities and reward values. In both cases, hypothetical blue-on-blue engagements are assigned large negative values to indicate the counter-productivity of such actions. Over a large number of engagements these measures provide a fair evaluation of the goodness of the picture used in the decision process.

Our approach to measure the impact of MOPs (measures of performance of functions or systems) causally on MOEs (measures of effectiveness for mission goals) suggests the following analogy: if the results (MOEs) of decisions and missions are identified as the effects, and the picture and system qualities (MOPs) as causes, then one can say that we causally measure the value, usefulness or goodness of a tactical picture and a C3IS to commanders' decisions and missions.

The specialization to the over-the-horizon hostile picture increases the discrimination capacity of the measures proposed by focusing on the value of this part of the picture for commanders' OTH-T. However, DREV MBMs are not limited to this aspect: they can be adapted for the estimation of types of contacts or conditions identifiable in the raw data from instrumented military exercises for corresponding types of actions or missions. We just need to adapt the model-based measures to what we want to measure, precisely and accurately.

For example, the proposed models accurately measure the relative improvements due to changes, but since we do not have a well-established level of picture quality needed for a particular mission, the measures cannot deliver an absolute measure of goodness. In addition, they do not assess the damage inflicted to hostile ships. On the other hand, from the application of these measures to a set of several exercises (at least four), it would be possible to infer the minimum information quality and systems performance required for that specific type of decision or mission. This minimum requirement could be expressed in terms of action/mission success rates or risks of failure, giving a probabilistic indication that at this information quality level, for a given class of mission scenarios, mission success is in excess of a given percentage, say 80%.

A MBM for the WANTAP completeness measure has been proposed and a clear distinction shown between the proposed measures and traditional ones: the new measures are geared at evaluating the effectiveness of a WANTAP for a specific mission, rather than at investigating some particular system performance parameter such as communication delay. Further studies are needed to explore model-based measures for other mission goals such as drug interdiction or area control.

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## APPENDIX A

### GLOSSARY

ambiguity	A sensor report that a wide-area correlator/tracker (C/T) system has processed but has been unable to place into a constructed track. The inability to determine if sensor reports are for a new track or are updates to an existing one.
ambiguous track	A track that cannot be automatically associated and fused with a known track in the C2 system track database. It may be a new track or it may be a known one that cannot be associated because the POSIT report contains corrupted, incorrect or insufficient information. Ambiguous tracks must be dealt with manually by the C2 system operator.
assumed friend	A track that is assumed to be a friend because of its characteristics, behavior or origin.
attribute	Any piece of information that increases the knowledge of a contact under surveillance.
causal relation	Relationship that directly links effects to their causes.
classification	In surveillance, the process of assigning an agreed-upon attribute such as allegiance for operations, e.g., neutral, hostile or faker.
constructed track	The subset of sensor reports considered by a C/T to belong to the same object, platform or track.
containment ellipse	A probability ellipse indicating the area where a contact (for example a ship) is located, with a given probability, e.g., 0.8 or 80%.

correlated-track data	Data resulting from correlation or tracking, or both.
correlation	Level of closeness among a subset of sensor reports that is used to assign reports to a given contact. The level of confidence of contact information increases as further statistically independent reports are correlated.
data fusion	The combining of data from multiple sources, or from the same source over a period of time, into a unified representation of the entities (units and events) described by those sources. The fused information represents an entity in greater detail and with less uncertainty than is obtainable from any of the original sources. Data fusion includes the processes of alignment, correlation, association and combination.
dead reckoning	Positional estimation of a mobile unit at a future time from the position and speed observed at sensor time, assuming no maneuvering; a tactical and navigation aid.
duplicated track	The situation in which a single observed unit gives rise to two separate tracks in the C2 system database. Duplicated tracks must generally be resolved manually by the C2 system operator. Misspelling of unit names is a typical cause.
engage	To take action, such as firing a missile, against a target that has been identified "hostile" in the tactical database.
extraneous track	A track in the C2 system track database for which there is no corresponding real unit. It is often made up of segments of tracks from several real units, especially if these units are moving in convoy.
faker	A friendly track acting as a hostile for exercise purposes.

friend	A track belonging to a declared friendly unit or nation.
farthest-on-circle	A decision-aid circle that expands from a reported contact position and time at a selected speed; it is used to estimate the area within which the contact might be at subsequent times.
ground-truth track	Track information that is used as a reference for other systems; it may include an accurate position of the platform.
hostile	A track that is eligible to be engaged.
identification	In surveillance, determination of an identity attribute by source data, intelligence reports or from the behavior of the object(s) of a track.
interoperability	Capabilities of systems, functions, people and information that allow effective interaction and joint operations. Several international organizations spend considerable effort to improve and maintain this capability across different meta-systems. The focus in the context of this report is on information, functions, systems, procedures, protocols and their management in a distributed situation for WANTAP compilation.
joker	A friendly track acting as a "suspect" for exercise purposes.
"kilo"	A friendly track of special interest.
level of significance	For one test or a set of statistical tests, the rate or probability at which statistical test results reject the hypothesized probabilistic model (by chance only) when the model is actually true.

link	Any means of communications between system components or users, mainly radio and satellite communications for WANTAP-related information systems.
Link [xx]	One of the NATO military radio communications standards for data and related functions (data dictionaries, message formats, procedures, communications protocols, coding, modulation). Examples include Link 11 (equivalent to the USN's TADIL-A or NTDS), Link 16 and Link 4.
local-area picture (LAP)	The picture developed by the ship's own sensors, i.e., organic information. This information is controlled and collected by assets under the ship's command direct control and is usually real-time. Under Link 11, combining the information from all participants in a given Link 11 network extends the LAP area. This effectively increases the horizon of each ship's organic picture.
maritime-tactical picture (MTP)	The picture (tactical information) necessary to support Allied maritime operations over the area of interest (AOI) of the maritime force commander (CTF). This may range from a specific ocean area to an overall global picture. The MTP is a combination of the local-area picture (LAP) and the wide-area picture (WAP). The MTP is the common (or recognized) picture that includes both organic and non-organic information. Future systems will integrate all this information and the distinction between the LAP and the WAP will disappear. The need to distinguish between organic versus non-organic information will be reduced.

metasystems	Systems made up of several systems or the logical and functional equivalent of a complex combination of system-to-human interactions. It also refers to the scientific application of systems methodologies that address systems in breadth and depth for all strata and aspects. From a human factor aspect, it studies multi-phase, multi-level and multi-paradigmatic creative problem-solving process for individuals, often in large groups. One primary goal is to study, design and then implement, in a cost-effective fashion, metasystems that are user-responsive.
neutral	A track whose characteristics, behavior, origin or nationality indicate that it is neither supporting nor opposing friendly forces.
non-organic asset, source or sensor	Assets that are not under the direct control of a given command organization, as opposed to organic assets, which are under its direct control.
non-organic information	Information collected by non-organic assets (sensors and agents). It comes from sources not under the direct control of the commander at the command level under consideration.
non-unique ID attribute	An ID that is unique at a high level for which low-level attributes correspond to several units.
nonparametric	A statistical test that does not require the estimation of the parameters or distribution of the hypothesized population.

order statistic	A statistic that requires the observations to be ordered (by size, color, attribute, alphabetically, numerically, etc.). The ordered sequence is then compared with the hypothesized sequence order. This comparison, using a given algorithm, forms one of the many order statistics. For simple hypotheses and small sample sizes, exact significance levels can be obtained with tests based on binomial or multinomial laws.
organic asset, source or sensor	Assets under direct operational control of a given command organization.
organic information	Information from sources under the control of a commander at a given level.
picture quality (PQ)	A measure of (i) the completeness of the picture, (ii) the positional accuracy of the tracks, (iii) the correctness of the track attributes, (iv) the timeliness of the track reports, and (v) the absence of extraneous, ambiguous and duplicated tracks.
procedure	The manner in which particular courses of action are taken to achieve an objective. In general they contain all of the steps that must be followed, whether manually or automatically, to ensure that the correct action is taken, in accord with the rules on which they are based.
rule	The principles or regulations on which procedures are formulated. They must account for the conditions that are likely to be faced when practicing procedures. The rules that are formulated for future command, control, communications and intelligence (C3I) systems will have to account for all the conditions that determine parameters such as track quality, confidence levels, classification, track numbering and a host of other factors pertinent to the target acquisition and fusion processes.

sensor report	A data report generated by a sensor or an information source pertaining to a contact, platform or group of platforms.
statistical inference	The process of extrapolating from statistics on a sample to the whole population of possible samples, at a given significance level.
suspect	A track that is potentially hostile (because of its characteristics, behavior, origin or nationality).
target	A contact report that is the object of surveillance based on an algorithm, automatic or manual. A qualification given to a contact that is under the scrutiny of an observer, an algorithm or a process necessary to develop a clear MTP. A contact target may have a large variety of possible identities in a real system, as compared to the specific identity (neutral, friend, hostile) attributed in a ground-truth file.
track and tracking	Exploitation of a sequence of reports from one or several spatially distributed sensors or other sources of information, to deduce a contact position at an arbitrary time in the past, present and future.
track handover	In data fusion, the process of transferring the responsibility for producing a track from one unit to another (human operators and/or processes).
unique ID attribute	An attribute that is sufficient to identify the class to the unit level.
unknown	An evaluated track which has not yet been identified.

wide-area picture	The picture developed using assets not under CTF direct control, e.g., shore-based assets and space-borne sensors. The volume of this information was once small, but it has increased over time to the point that special information dissemination architectures are now required, e.g., the current USN Force Over-the-horizon Track Coordinator (FOTC) used with JMCIS-Afloat and the Officer in Tactical Command Information eXchange System (OTCIXS).
zombie	A "suspect" air track conforming to ATC rules or flying a recognized traffic path.

## APPENDIX B

### ACRONYMS AND ABBREVIATIONS

AAW	anti-air warfare <sup>†</sup>
AAWC	Anti-air Warfare Commander
ACIXS	<u>A</u> llied <u>C</u> ommand <u>I</u> nformation <u>E</u> xchange <u>S</u> ystem <sup>††</sup>
AHWG	Ad-hoc Working Group
AMIME	AUS-CAN-NZ-UK-US <u>A</u> d-hoc Working Group on the <u>m</u> anagement of organic and non-organic <u>i</u> nformation in a <u>m</u> aritime <u>e</u> nvironment
AOI	area of operational interest
AOU	area of uncertainty
ARE	Admiralty Research Establishment, now DRA (UK)
AREC	Air Resource Element Commander
ASTAB	<u>a</u> utomatic <u>s</u> tatus <u>b</u> oard
ASUW	<u>a</u> nti- <u>s</u> urface <u>w</u> arfare
ASUWC	<u>A</u> nti- <u>S</u> urface <u>W</u> arfare <u>C</u> ommander
ASW	<u>a</u> nti- <u>s</u> ubmarine <u>w</u> arfare
ASWC	<u>A</u> nti- <u>s</u> ubmarine <u>W</u> arfare <u>C</u> ommander
ATC	air traffic control
AUS	<u>A</u> ustralia
AUS-CAN-NZ-UK-US	Counterpart of the NATO TTCP information exchange agreement for operational and in-development systems, related standards and problems. Member countries: <u>A</u> ustralia, <u>C</u> anada, <u>N</u> ew <u>Z</u> ea-land, <u>U</u> nited <u>K</u> ingdom and <u>U</u> nited <u>S</u> tates.
b-pdf	bivariate-probability density function
BG	Battle Group
BLOS	beyond line-of-sight (radio-wave propagation)
C/T	correlator/tracker
C2	command and control
C2IR	Command And Control Information Requirement (a UK-NISAS tool)
C3	command, control and communications

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<sup>†</sup> Capitals are used only when required, e.g., for the name of a specific system or group.

<sup>††</sup> Underlining is used only when the result does not follow a simple abbreviation rule.

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C3I	command, control, communications and intelligence
C3IS	communications, command, control and information system
CAN	<u>Canada</u>
CAS	center of the area to be scrutinized
CDS	combat direction system
CIS	communications and information system
civ	convolution-integration value
COF	cost of firing
COI	contact of interest
COP	common operating picture
CRWG	Copernicus Requirements Working Group (US)
CS	commander of an armed ship, or the ship effecting the weapon engagement in OTH-T
CTF	Commander Task Force
CTG	Commander Task Group
CUA	circular-uncertainty area
CVBG	Carrier Vehicle Battle Group (US)
CWC	Composite Warfare Commander
DLRP	data link reference position
DMCS	Director Maritime Combat Systems (CAN), now DMSS
dmi	<u>data mile</u> , defined as 6 000 ft (1 828.8 m)
DMSS	Director Maritime Ship Support (CAN)
DR	dead reckoning
DRA	Defence Research Agency (UK)
DREV	Defence Research Establishment Valcartier (CAN)
edc	error detection code (sometimes used for error detection and correction code).
ELINT	<u>electronic intelligence</u>
ESM	electronic support measures / warfare support measures
FDDS	Flag Data Display System (US)
FOSP	Fleet Ocean Surveillance Product (UK)
FOTC	Force Over-the-horizon Track Coordinator (US)
FSM	finite-state machine
GCCS	Global Command and Control System (US)
GDFS	Graphic Data Fusion System (US)
GEM	general-engagement measure
GEO	general-engagement opportunity
GRW	general-reward value
GT	ground-truth

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HB5	<u>Handbook 5</u> planned by AUS-CAN-NZ-UK-US
HB5D	<u>Handbook 5 Draft</u>
HEAT	Headquarters Effectiveness Assessment Tool (US)
HF	high frequency
HIT	high interest tracks
HP	hit probability
HQ	<u>headquarters</u>
ID	<u>i</u> dentification. Preferably unique for a given system or command stratum, since each stratum is distributed but different codes can exist among strata. It is considered a track attribute although it serves no track or contact-report function other than management.
IDU	interface-data unit
IEEE	Institute of Electrical and Electronics Engineers
IERs	information exchange requirements
IES	ideal engagement situation
IH	intended hostile
IM	information management
ISAR	Inverse Synthetic Aperture Radar (US)
ISAT	Information Systems Architecture Tool (UK-NISAS)
ISO	International Organization for Standardization
ITO	intended target opportunity
ITO-D	ITO-delay
ITO-D-P	ITO-delay-prediction
ITO-O	ITO-optimal
JMCIS	Joint Maritime Command Information Strategy (CAN)
JMCIS	Joint Maritime Command Information System (US), it includes NTCS-A and some interfaces.
JOTS	Joint Operational and Tactical System (US), JOTS II is the core program in NTCS-A.
LAP	local-area picture
Link [xx]	A NATO military radio communication standard for data and related functions, e.g., Link 11 (equivalent to USN's TADIL-A or NTDS), Link 16, Link 4
LIVEX	<u>live exercise</u>
LOB	line of bearing
LOS	line-of-sight (radio-wave propagation)
MARCOT	<u>M</u> aritime <u>C</u> ommand <u>O</u> perational <u>T</u> raining exercise (CAN)
MBM	model-based measure / mesure basée sur des modèles

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MCOIN	<u>M</u> aritime <u>C</u> ommand <u>I</u> nformation system (CAN)
MDE	mesure d'efficacité
MDP	mesure de performance
mi	statute <u>m</u> ile: 5 280 ft (1 609.35 m)
MIDAS	Maritime Intelligence Dissemination and Analysis System
min	<u>m</u> inute
MIST	Maritime Intelligence Support Terminal (AUS)
MMI	man-machine interface
MOE	measure of effectiveness for a mission goal
MONIME	<u>M</u> anagement of <u>O</u> rganic and <u>N</u> on-organic <u>I</u> nformation in a <u>M</u> aritime <u>E</u> nvironment, a program
MOP	measure of performance of a function or system
MSC	mission success criteria
MTP	maritime tactical picture
MTST	maneuvering target statistical tracker
N-KRS	Naval Knowledge-based Replanning Systems (US)
NATO	North Atlantic Treaty Organization
Navcomms	<u>N</u> aval <u>C</u> ommunications <u>C</u> ommittee of AUS-CAN-NZ-UK-US
NCCOSC	Naval Command, Control and Ocean Surveillance Center (US)
NDHQ	National Defence Headquarters (CAN)
NISAS	Naval Information Systems Architecture Study (UK)
nmi	international <u>n</u> autical <u>m</u> ile: 1 852 m
NOSC	Naval Ocean Systems Center, now NCCOSC (US)
NRAD	Naval Research and Development (US)
NTCS-A	Naval Tactical Command System - Afloat (US)
NTDS	Naval Tactical Data System (US), i.e., Link 11
NZ	New Zealand
OPFOR	<u>o</u> pposing <u>f</u> orces
OSI	Open Systems Interconnection
OTCIXS	<u>O</u> fficer in <u>T</u> actical <u>C</u> ommand <u>I</u> nformation <u>E</u> xchange <u>S</u> ystem
OTG	<u>O</u> ver-the-horizon <u>T</u> argeting <u>G</u> old (a message format)
OTH-DC&T	over-the-horizon detection, classification & targeting
OTH-T	over-the-horizon targeting
OTCIXS	<u>O</u> fficer in <u>T</u> actical <u>C</u> ommand <u>I</u> nformation <u>E</u> xchange <u>S</u> ystem
PC	picture consistency
pdf	probability density function
ph	probability of hitting a given target
phn	probability of hitting nothing
phs	probability of hitting something

pm	probability mass
POE	pertinence of engagement
POE-D	POE-delay
POE-D-P	POE-delay-prediction
POE-O	POE-optimal
POST	Prototype Ocean Surveillance Terminal (US)
PQ	picture quality
PRI	pulse repetition interval
PRV	pertinence reward value
QIER	quantified information exchange requirement
QIR	quantified information requirement
R&D	research and development
RAN	Royal Australian Navy
REPEAT	<u>Re</u> peatable <u>P</u> erformance <u>E</u> valuation and <u>A</u> nalysis <u>T</u> ool (US)
RESA	Research, Evaluation and Systems Analysis War-gaming Facility (US)
RF	radio frequency
RIMPAC	<u>R</u> im of the <u>P</u> acific (In this document it refers to a naval LIVEX of Pacific Rim countries)
RMP	recognized maritime picture
RN	Royal Navy (UK)
ROEs	rule(s) of engagements
SAG	Surface Action Group
SEDSCAF	standard ELINT data systems codes and format (US)
SEM	specific engagement measure
SEO	specific engagement opportunity
SEWC	<u>S</u> pace and <u>E</u> lectronic <u>W</u> arfare <u>C</u> ommander (Proposed by US)
SPAWAR	<u>S</u> pace and Naval <u>W</u> arfare Systems Command (US)
SRW	specific reward value
STANAG [xx]	NATO <u>s</u> tandardization <u>a</u> greement
STU	secure telephone unit
STWC	<u>S</u> trike <u>W</u> arfare <u>C</u> ommander
SUBOPAETH	<u>S</u> ubmarine <u>O</u> perating <u>A</u> uthority (US)
SWAN	Secure Wide Area Network
TADIL-A	<u>T</u> actical <u>D</u> ata <u>I</u> nformation <u>L</u> ink - <u>A</u> float, i.e., Link 11
TADIXS	<u>T</u> actical <u>D</u> ata <u>I</u> nformation <u>E</u> xchange <u>S</u> ystem
TASM	Tomahawk Anti-ship Missile (US)
TC	track continuity
tciv	total (value) of convolution-integration values

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TDP	tactical data processor
TIMEX	<u>T</u> actical <u>I</u> nformation <u>M</u> anagement <u>E</u> xercise (US)
TIMSIM	<u>T</u> actical <u>I</u> nformation <u>M</u> anagement <u>S</u> imulation (AUS-CAN-NZ-UK-US)
TLWR	top level warfare requirements (US)
TP	track purity
TPQ	tactical picture quality
TRV	target reward value
TTCP	the Technical Cooperation Program
TUA	target-uncertainty area
TWCS	Tomahawk Weapons Control System (US)
UK	United Kingdom
US	United States
USN	US Navy
WANTAP	<u>w</u> ide- <u>a</u> rea <u>n</u> aval <u>t</u> actical <u>p</u> icture
WANTAP Task	Analysis of <u>W</u> ide- <u>a</u> rea <u>N</u> aval <u>T</u> actical <u>P</u> icture <u>T</u> ask (CAN)
WAP	wide-area picture
WAPS	wide-area picture systems like JOTS, TWCS, JMCIS and GCCS
WGS	World Geodetic System
WT-C	<u>w</u> ide- <u>a</u> rea <u>t</u> racke <u>r</u> - <u>c</u> orre <u>l</u> ator
WUA	weapon-uncertainty area

**APPENDIX C**  
**SUMMARY TABLES OF RESULTS**

**Intersection Rates**

**Pertinence-of-engagement Measure**

**Intended-target-opportunity Measure**

**Delays**

**Positional Errors (all cases)**

**Positional Errors (outliers removed)**

## Intersection Rates - Summary

WANTAP day	TWCS (%)	FOTC (%)	SAG1 (%)	SAG2 (%)
1	98.6	91.9	82.9	85.3
2	90.1	91.2	88.9	82.0
3	90.5	68.8	74.0	69.1
4	89.4	86.8	89.1	87.3
Overall	91.1	84.6	84.2	81.1

TABLE 1 - TIMSIM '93 intersection rate % (no delay)

WANTAP day	TWCS (%)	FOTC (%)	SAG1 (%)	SAG2 (%)
1	42.9	56.4	47.2	47.7
2	72.0	71.3	53.4	33.9
3	62.7	41.5	41.3	46.6
4	61.8	58.4	41.6	51.6
Overall	62.3	58.0	45.7	46.3

TABLE 2 - TIMSIM '93 intersection rate % (delay without DR prediction)

WANTAP day	TWCS (%)	FOTC (%)	SAG1 (%)	SAG2 (%)
1	31.4	41.8	46.0	38.4
2	57.4	55.2	36.0	18.2
3	47.5	40.0	34.3	34.4
4	45.7	40.4	26.3	46.3
Overall	47.5	45.1	33.8	36.5

TABLE 3 - TIMSIM '93 intersection rate % (delay with DR prediction)

**Pertinence-of-engagement Measure - Summary**

<b>WANTAP day</b>	<b>TWCS (-2.5, 0.5)</b>	<b>FOTC (-2.5, 0.5)</b>	<b>SAG1 (-2.5, 0.5)</b>	<b>SAG2 (-2.5, 0.5)</b>
1	0.34	0.37	0.43	0.30
2	0.32	0.17	0.16	0.12
3	0.12	-0.03	0.00	-0.07
4	0.10	0.19	0.22	0.15
<b>Overall</b>	0.20	0.16	0.17	0.12

TABLE 1 - TIMSIM '93 pertinence-of-engagement measure (no delay)

<b>WANTAP day</b>	<b>TWCS (-2.5, 0.5)</b>	<b>FOTC (-2.5, 0.5)</b>	<b>SAG1 (-2.5, 0.5)</b>	<b>SAG2 (-2.5, 0.5)</b>
1	-0.28	-0.18	-0.14	-0.21
2	-0.10	-0.17	-0.34	-0.46
3	-0.24	-0.35	-0.38	-0.41
4	-0.29	-0.30	-0.41	-0.18
<b>Overall</b>	-0.22	-0.25	-0.34	-0.30

TABLE 2 - TIMSIM '93 pertinence-of-engagement measure (delay without DR prediction)

<b>WANTAP day</b>	<b>TWCS (-2.5, 0.5)</b>	<b>FOTC (-2.5, 0.5)</b>	<b>SAG1 (-2.5, 0.5)</b>	<b>SAG2 (-2.5, 0.5)</b>
1	-0.33	-0.34	-0.24	-0.30
2	-0.27	-0.24	-0.42	-0.48
3	-0.27	-0.36	-0.43	-0.48
4	-0.39	-0.43	-0.48	-0.22
<b>Overall</b>	-0.32	-0.34	-0.42	-0.35

TABLE 3 - TIMSIM '93 pertinence-of-engagement measure (delay with DR prediction)

## Intended-target-opportunity Measure - Summary

WANTAP day	TWCS [-2.5, 0.5]	FOTC [-2.5, 0.5]	SAG1 [-2.5, 0.5]	SAG2 [-2.5, 0.5]
1	0.32	0.32	0.34	0.25
2	0.28	0.17	0.15	0.10
3	0.10	-0.10	-0.05	-0.12
4	0.07	0.15	0.19	0.12
Overall	0.17	0.12	0.13	0.08

TABLE 1 - TIMSIM '93 intended-target-opportunity measure (no delay)

WANTAP day	TWCS [-2.5, 0.5]	FOTC [-2.5, 0.5]	SAG1 [-2.5, 0.5]	SAG2 [-2.5, 0.5]
1	-0.29	-0.22	-0.18	-0.24
2	-0.11	-0.17	-0.34	-0.46
3	-0.25	-0.37	-0.40	-0.43
4	-0.30	-0.32	-0.41	-0.19
Overall	-0.23	-0.27	-0.36	-0.31

TABLE 2 - TIMSIM '93 intended-target-opportunity measure (delay without DR prediction)

WANTAP day	TWCS [-2.5, 0.5]	FOTC [-2.5, 0.5]	SAG1 [-2.5, 0.5]	SAG2 [-2.5, 0.5]
1	-0.35	-0.36	-0.29	-0.32
2	-0.28	-0.24	-0.43	-0.48
3	-0.29	-0.38	-0.45	-0.49
4	-0.40	-0.44	-0.49	-0.23
Overall	-0.33	-0.35	-0.43	-0.37

TABLE 3 - TIMSIM '93 intended-target-opportunity measure (delay with DR prediction)

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## Delays - Summary

<b>Allegiance</b>	<b>TWCS</b>	<b>FOTC</b>	<b>SAG1</b>	<b>SAG2</b>
Hostile	46.63	23.87	50.15	43.77
Friendly	47.74	15.57	25.63	25.38
Neutral	54.75	19.41	47.32	37.66
<b>Overall</b>	51.07	18.79	37.67	35.15

Day 1 - TIMSIM '93 mean differences between position time and report time

<b>Allegiance</b>	<b>TWCS</b>	<b>FOTC</b>	<b>SAG1</b>	<b>SAG2</b>
Hostile	14.90	16.09	24.71	32.62
Friendly	7.94	15.58	26.01	28.81
Neutral	15.78	23.87	28.71	44.22
<b>Overall</b>	12.95	19.25	26.82	34.54

Day 2 - TIMSIM '93 mean differences between position time and report time

<b>Allegiance</b>	<b>TWCS</b>	<b>FOTC</b>	<b>SAG1</b>	<b>SAG2</b>
Hostile	18.66	21.75	27.82	30.07
Friendly	8.52	5.56	19.35	16.56
Neutral	14.35	24.90	34.73	26.25
<b>Overall</b>	13.46	18.38	28.94	25.04

Day 3 - TIMSIM '93 mean differences between position time and report time

<b>Allegiance</b>	<b>TWCS</b>	<b>FOTC</b>	<b>SAG1</b>	<b>SAG2</b>
Hostile	14.74	19.18	25.58	23.33
Friendly	7.88	10.85	16.28	14.05
Neutral	12.09	28.70	37.10	41.37
<b>Overall</b>	11.62	21.58	28.74	27.56

Day 4 - TIMSIM '93 mean differences between position time and report time

**Positional Errors at Position Time (all cases) - Summary**

<b>Allegiance</b>	<b>TWCS</b>	<b>FOTC</b>	<b>SAG1</b>	<b>SAG2</b>
Hostile	2.09	13.66	17.87	109.53
Friendly	0.83	1.11	1.33	12.39
Neutral	26.41	12.58	5.61	32.76
<b>Overall</b>	<b>14.76</b>	<b>7.49</b>	<b>5.23</b>	<b>34.09</b>

Day 1 - TIMSIM '93 mean differences between reported position and GT position

<b>Allegiance</b>	<b>TWCS</b>	<b>FOTC</b>	<b>SAG1</b>	<b>SAG2</b>
Hostile	52.76	110.30	205.78	195.51
Friendly	0.75	2.08	2.27	2.95
Neutral	12.64	47.91	56.12	55.35
<b>Overall</b>	<b>15.54</b>	<b>35.21</b>	<b>38.76</b>	<b>34.83</b>

Day 2 - TIMSIM '93 mean differences between reported position and GT position

<b>Allegiance</b>	<b>TWCS</b>	<b>FOTC</b>	<b>SAG1</b>	<b>SAG2</b>
Hostile	20.44	74.09	70.38	76.18
Friendly	1.06	2.38	2.15	1.98
Neutral	14.79	35.76	39.09	144.78
<b>Overall</b>	<b>11.73</b>	<b>31.07</b>	<b>32.30</b>	<b>40.29</b>

Day 3 - TIMSIM '93 mean differences between reported position and GT position

<b>Allegiance</b>	<b>TWCS</b>	<b>FOTC</b>	<b>SAG1</b>	<b>SAG2</b>
Hostile	9.79	45.48	28.08	60.16
Friendly	1.05	0.95	2.36	3.02
Neutral	16.91	18.68	30.17	25.46
<b>Overall</b>	<b>9.56</b>	<b>20.12</b>	<b>21.57</b>	<b>25.69</b>

Day 4 - TIMSIM '93 mean differences between reported position and GT position

**Positional Errors at Position Time (outliers removed) - Summary**

<b>Allegiance</b>	<b>TWCS</b>	<b>FOTC</b>	<b>SAG1</b>	<b>SAG2</b>
Hostile	2.09	1.30	1.19	1.03
Friendly	0.83	1.11	1.33	1.63
Neutral	3.86	1.40	0.94	1.25
<b>Overall</b>	<b>2.76</b>	<b>1.25</b>	<b>1.20</b>	<b>1.44</b>

Day 1 - TIMSIM '93 mean differences between reported position and GT position

<b>Allegiance</b>	<b>TWCS</b>	<b>FOTC</b>	<b>SAG1</b>	<b>SAG2</b>
Hostile	4.02	5.41	4.82	7.64
Friendly	0.75	1.50	1.82	2.48
Neutral	0.98	1.75	1.19	1.22
<b>Overall</b>	<b>1.36</b>	<b>1.95</b>	<b>1.61</b>	<b>2.31</b>

Day 2 - TIMSIM '93 mean differences between reported position and GT position

<b>Allegiance</b>	<b>TWCS</b>	<b>FOTC</b>	<b>SAG1</b>	<b>SAG2</b>
Hostile	3.14	5.47	5.28	4.45
Friendly	1.06	1.94	2.15	1.98
Neutral	1.67	1.88	1.74	0.57
<b>Overall</b>	<b>1.82</b>	<b>2.64</b>	<b>2.62</b>	<b>2.95</b>

Day 3 - TIMSIM '93 mean differences between reported position and GT position

<b>Allegiance</b>	<b>TWCS</b>	<b>FOTC</b>	<b>SAG1</b>	<b>SAG2</b>
Hostile	2.72	3.26	2.90	3.96
Friendly	1.05	0.95	2.36	3.02
Neutral	1.49	2.05	2.05	2.76
<b>Overall</b>	<b>1.76</b>	<b>2.00</b>	<b>2.36</b>	<b>3.14</b>

Day 4 - TIMSIM '93 mean differences between reported position and GT position

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This document presents new methods for studying, analyzing and assessing the value, usefulness or goodness of the tactical information used by commanders in their decision process. These methods relate information quality and system measures of performance (MOPs) to decision and mission measures of effectiveness (MOEs). Finer-grained processing of relevant military exercise data results in hundredfold increases in sample sizes; this in turn improves the statistical significance and accuracy of the estimated MOPs and MOEs. The new DREV model-based measures (MBMs) use simple decision models to assess the value, usefulness or goodness of the picture a commander uses for a decision or a mission. The version of the DREV MBMs defined in this document focus on afloat-command information systems capabilities for supporting commander over-the-horizon targeting. However, they could evolve into measures for other missions such as search and rescue or area control, and furthermore into powerful real-time decision aids.

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Command and Control, Information systems  
Measure(s) of Performance, MOP(s)  
Measure(s) of Effectiveness, MOE(s)  
Causal Relation, Causality  
Wide-Area Naval Tactical Picture, Picture Quality  
Decision Models, Decision Aids, Utility  
Model-Based Measures  
Engagement Opportunity  
Data Fusion  
Measure of Goodness  
Information Management  
Reward Values  
Information goodness or usefulness

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